Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

(2)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

AD-A207 929

1b. RESTRICTIVE MARKINGS	DTIC FILE COPY
3. DISTRIBUTION/AVAILABILITY OF REPORT	Approved for public release; distribution is unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	
5. MONITORING ORGANIZATION REPORT NUMBER(S)	AFOSR-TR- 89-0599
6a. NAME OF PERFORMING ORGANIZATION	Georgia Institute of Technology School of Aerospace Engineering
6b. OFFICE SYMBOL (If applicable)	
7a. NAME OF MONITORING ORGANIZATION	AFOSR/NA
6c. ADDRESS (City, State, and ZIP Code)	Atlanta, Georgia 30332
7b. ADDRESS (City, State, and ZIP Code)	Building 410, Bolling AFB DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	AFOSR/NA
8b. OFFICE SYMBOL (If applicable)	NA
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	AFOSR 84-0082
8c. ADDRESS (City, State, and ZIP Code)	Building 410, Bolling AFB DC 20332-6448

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	2308	A1	

DTIC ELECTE MAY 1 6 1989 S E D

11. TITLE (Include Security Classification)
(U) Investigation of the Flame-Acoustic Wave Interaction ~~During Axial~~ Solid Rocket Instabilities

12. PERSONAL AUTHOR(S)
B.T. ZINN, U.G. HEGDE, J.I. JAGODA AND B.R. DANIEL

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
FINAL REPORT	FROM 2/1/86 TO 1/31/89	1989, MARCH 31	53

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Solid propellant rocket motors, combustion instability, premixed flames, diffusion flames, acoustic driving/damping

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report describes the research performed under AFOSR Grant No. 84-0082 during the period 2/1/86 - 1/31/89. The major objectives of the program were (i) to determine the characteristics of solid propellant gas phase flames in rocket motors experiencing axial instabilities and (ii) to determine the validity of state of the art solid propellant response models The program was divided into two tasks in order to achieve these objectives.

In Task I, the response of sidewall stabilized premixed flames to longitudinal, standing acoustic waves (which simulate the oscillations encountered in unstable rocket motors) was studied. A premixed flame was chosen for this first phase as it eliminated the need to deal with difficulties arising from the presence of diffusion processes in the flame (these were studied in Task II of the program) while providing a flame possessing many important features of actual solid propellant flames. A theoretical model of the unsteady behavior of such flames, based upon actual solid propellant response modes, was developed. Experimental

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☒ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr Mitat Birkan	22b. TELEPHONE (Include Area Code) (202)767-4937 / 22c. OFFICE SYMBOL AFOSR/NA

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

89 5 15 175

measurements of velocities and heat release rates as well as flow visualization studies were undertaken to check the applicability of the model and elucidate important features of the unsteady flame behavior. It was found that the effect of the flame driving or damping is manifested in sharp changes in the normal velocity fluctuation in the flame region. This "pumping" action results in the interchange of energy between the core flow oscillations and the unsteady flame processes. It was shown, for the first time, that the flame behaves as a combination of an acoustic monopole and an acoustic dipole. Close agreement between theory and experiment was demonstrated indicating that state of the art models of unsteady solid propellant flames are capable of predicting the flame-acoustic interactions during axial instabilities. Furthermore it was shown that the acoustic admittance at the propellant surface can exert considerable influence on the flame driving characteristics and that the unsteady heat transfer from the flame to the propellant surface may provide a feedback mechanism between propellant burn rate and the acoustic oscillations which provides the energy required to sustain axial instabilities.

During Task II, the effect of diffusion limited processes on the driving/damping of axial instabilities in solid propellant rocket motors was studied. This was accomplished by investigating the unsteady behavior of multiple diffusion flames stabilized on the sidewall of a duct. This configuration simulated the unsteady burning of sandwich type solid propellant flames. It was shown that such diffusion flames are responsive to axial acoustic oscillations and that the response is frequency dependent. A theoretical model of the unsteady behavior of acoustically excited diffusion flames was developed demonstrating that the effects of diffusion processes may be incorporated into models of unsteady solid propellant flame behavior. Finally, it was shown that the behavior of the excited diffusion flames is similar to the acoustic monopole-dipole combination behavior which was exhibited by the investigated premixed flames.

INVESTIGATION OF THE FLAME-ACOUSTIC WAVE INTERACTION DURING AXIAL SOLID ROCKET INSTABILITIES

Final Report

Prepared For

Air Force Office of Scientific Research

by

DTIC COPY INSPECTED

B. T. Zinn, U. G. Hegde, J. I. Jagoda and B. R. Daniel

SCHOOL OF AEROSPACE ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, GA 30332

AFOSR Grant No. AFOSR-84-0082

March 1989

AFOSR-TR- 89-0599

TABLE OF CONTENTS

ABSTRACT

This report describes the research performed under AFOSR Grant No. 84-0082 during the period February 1, 1986 through January 31, 1989. The major objectives of the program were (i) to determine the characteristics of solid propellant gas phase flames in rocket motors experiencing axial instabilities and (ii) to determine the validity of state of the art solid propellant response models. The program was divided into two tasks in order to achieve these objectives.

In Task I, the response of sidewall stabilized premixed flames to longitudinal, standing acoustic waves (which simulate the oscillations encountered in unstable rocket motors) was studied. A premixed flame was chosen for this first phase as it eliminated the need to deal with difficulties arising from the presence of diffusion processes in the flame (these were studied in Task II of the program) while providing a flame possessing many important features of actual solid propellant flames. A theoretical model of the unsteady behavior of such flames, based upon actual solid propellant response models, was developed. Experimental measurements of velocities and heat release rates as well as flow visualization studies were undertaken to check the applicability of the model and elucidate+ important features of the unsteady flame behavior. It was found that the effect of the flame driving or damping is manifested in sharp changes in the normal velocity fluctuation in the flame region. This "pumping" action results in the interchange of energy between the core flow oscillations and the unsteady flame processes. It was shown, for the first time, that the flame behaves as a combination of an acoustic monopole and an acoustic dipole. Close agreement between theory and experiment was demonstrated indicating that state of

the art models of unsteady solid propellant flames are capable of predicting the flame-acoustic interactions during axial instabilities. Furthermore, it was shown that the acoustic admittance at the propellant surface can exert considerable influence on the flame driving characteristics and that the unsteady heat transfer from the flame to the propellant surface may provide a feedback mechanism between propellant burn rate and the acoustic oscillations which provides the energy required to sustain axial instabilities.

During Task II, the effect of diffusion limited processes on the driving/damping of axial instabilities in solid propellant rocket motors was studied. This was accomplished by investigating the unsteady behavior of multiple diffusion flames stabilized on the sidewall of a duct. This configuration simulated the unsteady burning of sandwich type solid propellant flames. It was shown that such diffusion flames are responsive to axial acoustic oscillations and that the response is frequency dependent. A theoretical model of the unsteady behavior of acoustically excited diffusion flames was developed demonstrating that the effects of diffusion processes may be incorporated into models of unsteady solid propellant flame behavior. Finally, it was shown that the behavior of the excited diffusion flames is similar to the acoustic monopole-dipole combination behavior which was exhibited by the investigated premixed flames.

INTRODUCTION

This report summarizes the research performed during the period February 1, 1986 through January 31, 1989 under AFOSR Grant No. AFOSR-84-0082 which is entitled "Investigation of the Flame-Acoustic Wave Interaction During Axial Solid Rocket Instabilities". The overall objectives of this research were (i) the determination of the characteristics of solid propellant gas phase flames in rocket motors experiencing axial instabilities and the contributions of these flames to the driving of the instabilities, and (ii) the determination of the validity of state of the art solid propellant response models. The problem is of much practical interest because it is well known that the interaction of solid propellant flames with the rocket flow oscillations is the mechanism responsible for driving the instability. Consequently, developing an understanding of the fundamental processes which control this interaction may lead to the development of practical means for reducing the driving provided by oscillatory solid propellant flames.

The characteristics of solid propellant flames depend upon the interaction between processes which occur in the gas and solid phases. During burning, heating from the gas phase leads to propellant surface pyrolysis. The gases leaving the surface continue reacting, in diffusion and premixed flames,[1,2] as they move away from the pyrolyzing surface. Some of the released thermal energy is transported back to the propellant surface to continue the burning process. The remainder of the released energy causes an increase in the temperature of the gases from an estimated 900°K at the propellant surface to, approximately, 3300°K at the outer edge of the flame.

In addition, momentum exchange with the axially moving core flow turns the gases leaving the surface in the direction of the combustor core flow. Consequently, the propellant burn rate depends upon gas and solid phase chemical kinetics, gas phase diffusion and mixing processes, gas and solid phase transport processes and so on.

It is evident, therefore, that the complexity of the solid propellant flame presents the investigator with a myriad of challenging problems which are compounded when the multidimensionality of the flow and the unsteady effects are taken into consideration. Moreover, even if theoretical models of these processes are developed,[3-7] they are not amenable to direct experimental verification. The problem lies in the extremely small dimensions of the solid propellant combustion zone. For example, the thickness of the solid phase thermal wave is of the order of 15 microns and that of the gas phase reaction zone is of the order of 50 microns.[1] Probing such thin zones with physical probes, or even available optical probes is not feasible. These difficulties are compounded by the short residence times of the material within the combustion zone which are of the order of 10^{-3} -10^{-6} seconds.[1] In addition, the smoky nature of the flame will hinder optical access to the propellant surface where combustion occurs.

To deal with this problem, this research program was divided into two tasks[8,9]. In Task I, the response of premixed flames stabilized on the sidewall of duct to the excitation of a longitudinal, standing acoustic waves (which simulate the behavior of the oscillations in solid propellant rockets experiencing axial instabilities) was studied. A premixed flame was chosen for Task I of this study because it eliminated the need to deal with difficulties arising from the presence of diffusive processes in the flame (these were studied in the second phase of the program) while providing the

investigator with a flame possessing many of the important features of actual solid propellant flames. For example, it possesses the sharp temperature rise between the propellant surface and the flame edge,[1] it interacts with temperature and velocity acoustic boundary layers which also exist next to burning solid propellant surfaces and it provides a situation in which an oscillatory, multidimensional flame region interacts with one dimensional core flow oscillations. In addition, the thicknesses of the investigated premixed flames could be controlled experimentally which provided one with an opportunity to perform the needed measurements.

The experimental set up used during Task I of this research program is shown schematically in Fig. 1. The investigated premixed, flat flame is stabilized above a porous plate burner on the lower apparatus wall which simulates a solid propellant surface. Acoustic drivers at one end of the apparatus are used to establish a standing acoustic wave of desired amplitude, frequency and pressure and velocity relationship in the vicinity of the flame. The behavior of the flame was investigated both theoretically and experimentally in order to determine the nature of its interaction with the adjacent oscillatory flow.

The investigation specifically addressed the following two questions:

1. Are state of the art models of unsteady solid propellant flames capable of predicting the characteristics of the developed premixed flame under conditions simulating those encountered in unstable rocket motors?
2. What features of the flame(e.g.,maximum flame temperature, heat transfer to the propellant surface, spatial and temporal distributions of the flame heat release rate and so on) exert the greatest influence upon the flame driving/damping of the core flow axial oscillations?

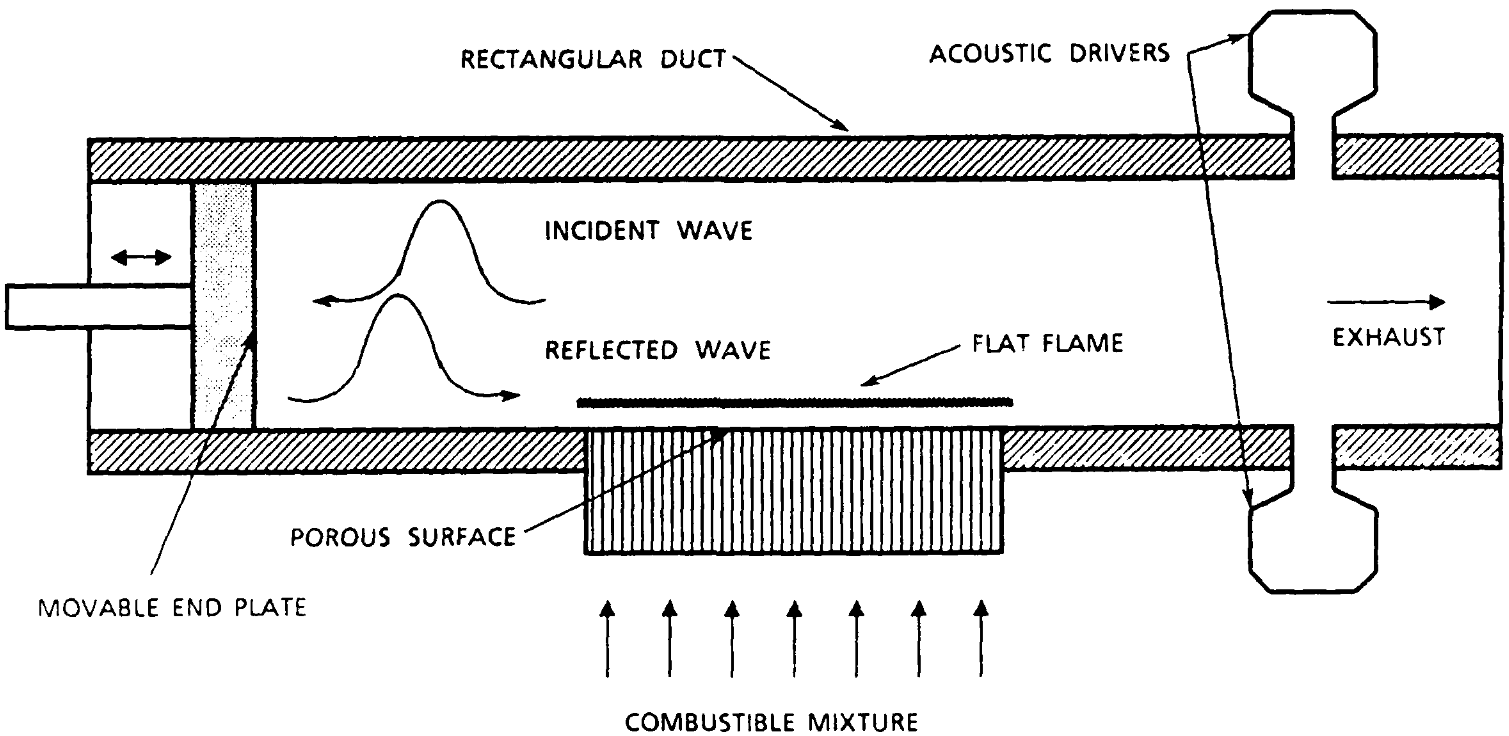


Fig. 1. Experimental Set-Up Schematic.

These questions were answered by a combination of theory and experiment. A theoretical model of the premixed flame experiencing axial acoustic oscillations was developed[10] on the basis of current, state of the art unsteady solid propellant flame analyses. The predictions of this model were compared with measurements of the spatial distributions of normal velocity and heat release rate and their phase relationships with the acoustic pressure oscillations. As will be discussed in the next section, these quantities are directly indicative of the acoustic driving/damping characteristics of the flame. It was found that the model predictions were in excellent agreement with the experimentally measured data. In particular, the model was able to predict both the frequency dependence as well as the magnitude of the flame driving. An important new finding was that acoustic driving occurs by a combination of a monopole and dipole type acoustic source behavior of the flame. This was corroborated by both theory and experiment. These findings and their implications are described in the next section. Obviously, these studies greatly enhance the confidence in the validity of the developed model and, therefore, in related models of unsteady solid propellant flames.

Although this agreement is most encouraging, it should be realized that diffusion processes which are an important facet of solid propellant combustion were not accounted for in the first phase of this program. These processes occur, in part, due to propellant heterogeneity[1] and they involve the diffusion of oxidizer and fuel towards each other. These diffusion processes are important as they often control the overall reaction rates.[11] Therefore, the studies initiated in the first phase of this research program were extended to investigate the behavior of carefully controlled diffusion flames stabilized in longitudinal acoustic fields.

Task II of the research also involved a close interaction between theoretical and experimental efforts. The experimental set up was modified by replacing the side wall porous plug burner(see Fig. 1) by a row of parallel, alternating fuel and oxidizer inlet ports simulating, for example, a sandwich type of propellant in which the oxidizer and binder portions alternate (see Fig. 2)*. Longitudinal sound fields excited by the acoustic drivers were imposed upon the established diffusion flames to simulate the unsteady environment in unstable rocket motors. As with the premixed flame set up, this configuration possessed many of the features of actual solid propellant flames. It simulated the sharp temperature rise between the solid propellant surface and the flame edge,[1] it interacted with the temperature and velocity acoustic boundary layers which also exist next to the burning solid propellant surface and so on. In addition, the important effects of diffusion processes in the flame region were included in the investigation.

The diffusion flame studies were conducted with the objective of answering the following questions:

1. How does the presence of diffusion processes in the flame region affect the acoustic driving/damping characteristics of the flame?
2. What features of the flame (e.g., the fuel/air ratio, flow rates, flame temperatures and so on) exert the greatest influence upon the flame driving/damping characteristics?

   How may the effect of diffusion processes be incorporated in theoretical models of unsteady solid propellant flames?

---

*Such sandwiches" of actual solid propellants have been utilized in the past to study solid propellant flames.[12]

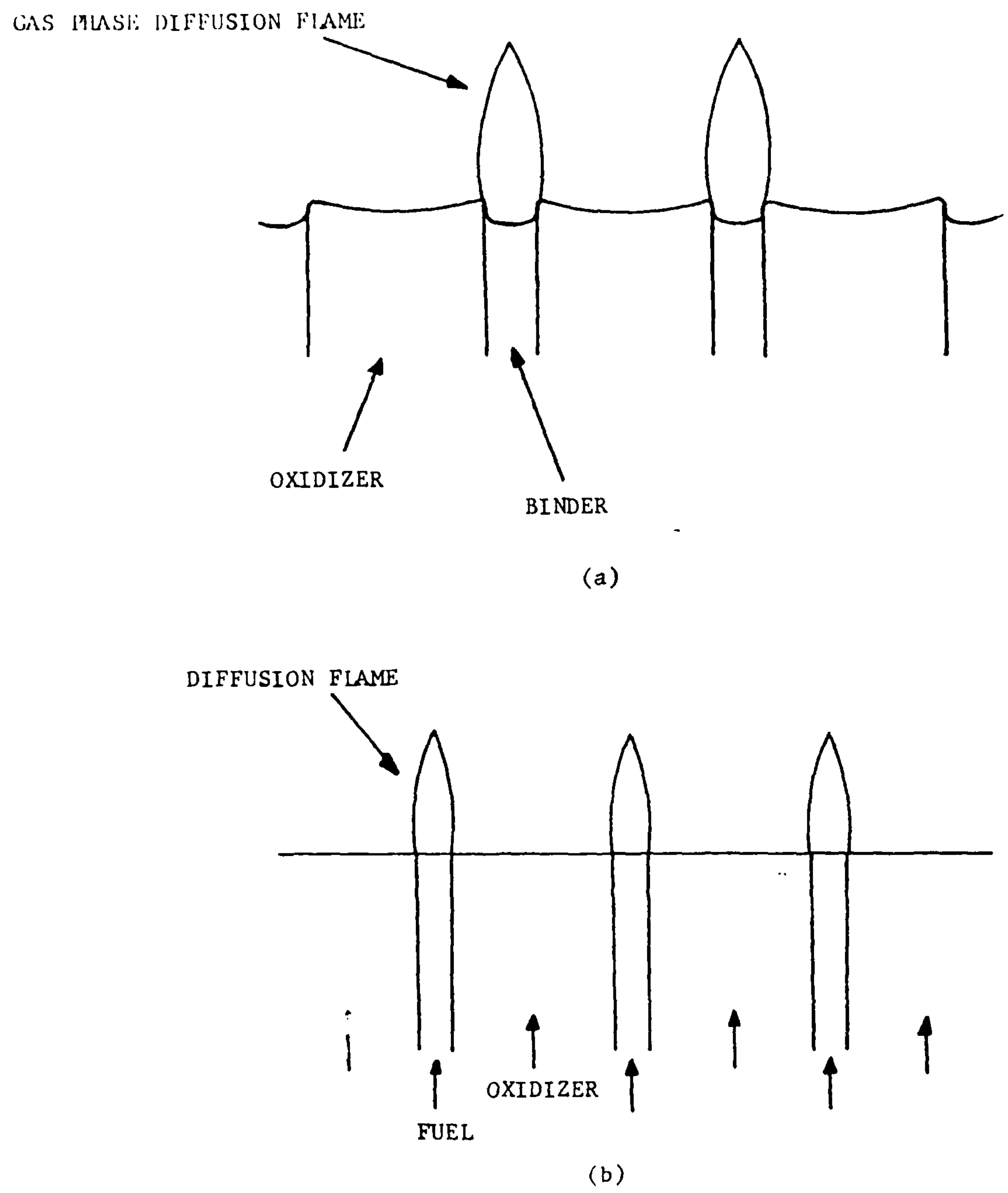


Fig. 2. (a) Sandwich Propellant with Established Gas Phase Diffusion Flames and (b) Proposed Simulation by Gaseous Diffusion Flames.

In the next section, the results obtained under both tasks of this program are described. The significance of these results is evaluated and important findings are summarized. Finally, Appendix A lists the personnel involved, the graduate degrees awarded, and the professional interactions made possible by this program.

RESEARCH ACCOMPLISHMENTS

This section describes the results obtained during the two tasks of the research program.

Task I:

Interaction of Premixed Flames with Axial Acoustic Fields

The developed experimental set up (see Figs. 1 and 3) allows the premixed flame to be stabilized sufficiently away from the wall so that the required measurements may be performed.[13-17] It is described in detail in Ref. 18. Briefly, the set up consists of a long rectangular tube having a flat flame burner on one of its side walls, an axially movable injecter plate at the inlet end and two acoustic drivers at the exhaust end.

During an experiment, a combustible mixture of propane and air is fed into the side wall burner and a flat flame is stabilized a short distance (i.e., 5-15 mm) away from the burner surface (see also Fig. 4). Next, the acoustic drivers are turned on to excite a standing longitudinal acoustic wave of desired frequency and amplitude in the tube. The position of the flame relative to the standing acoustic wave (i.e., next to a pressure node or pressure antinode) can be varied by moving the injector plate axially.

As the results obtained during this investigation are best described by comparing experimental and theoretical results, the theoretical model (described in detail in Ref. 10) will be briefly outlined. The flow variables including temperature, pressure, velocity, fuel mass fraction and so on are expressed as sums of steady and unsteady components. A set of nonlinear differential equations is obtained for the steady state components and a set of linear differential equations for the unsteady components. The analysis for the unsteady components is two dimensional and depends both upon the axial location (x) and the normal distance (y) from the burner surface. The equations for the unsteady components contain coefficients which depend upon the steady state solutions and are subject to boundary conditions at the burner surface ($y = 0$) and at the downstream edge of the flame ($y = y_f$). Thus, the steady state solutions need to be determined either theoretically or experimentally or by some combination of the two. In addition, some of the boundary conditions, in particular the value of the normal component of the velocity fluctuation, v', at the burner surface need to be input from experimental measurements.

The acoustic driving/damping characteristics of the investigated flames may be determined in two ways. First, the acoustic energy input (or extracted) by the flame from the core flow oscillations is given by the time average of the product $p'v'$ of the acoustic pressure p' and the normal component of the velocity fluctuation v'. In this connection, it should be pointed out that a normal component of the fluctuating velocity v' is formed in the flame region as a result of the periodic reaction rate (and expansion) of the flame. If the product $p'v'$ is positive, then energy is fed into the acoustic oscillations and vice versa. If all phases are referred to that of the acoustic pressure (as was done in the experiments) then the pressure

oscillations may be taken to be purely real. In such a case, the energy input of the flame is given by $< p' \text{ Real } (v')>$ which is the time average of the product of p' and the real part of v' generated by the flame. This yields a quantitative measure of the flame driving/damping characteristics. Secondly, a qualitative measure of the driving characteristics of the flame may be obtained using Rayleigh's criterion[19] which states that if the unsteady heat release from the flame is in phase with the local pressure oscillations, then acoustic driving by the flame results (and vice versa)> Both of these criteria were utilized in the conducted studies.

Comparisons Between Theory and Experiment

The model for the unsteady flame behavior requires the following input:

(i) steady state spatial distributions of the temperature, velocities and heat release rate.

(ii) the value of the normal velocity fluctuation v' at the burner surface $y = 0$.

In accordance with the statements made earlier about the driving/damping characteristics of the flame, attention will be focussed herein on the following predictions of the model:

(i) the distribution of the real part of the normal velocity fluctuation, Real (v') and

(ii) the distribution of the heat release rate fluctuation, q'.

The required steady state temperature and velocity distributions were obtained experimentally. The steady state temperature distribution was determined using the inclined slit method[8,20] while the velocities were measured using LDV. The steady state reaction rate (w) is related to the steady state temperature, T, by the following Arrhenius type relation

$$\bar{W} = A\frac{(1-\bar{T})^2}{\bar{T}^2}e^{-E/T}$$

where E is the (normalized) activation energy and A is the steric factor. As these quantities depend upon the overall reaction characteristics of the flame and are not readily available, the theoretical model was used, in the inverse mode, to determine these quantities; that is, instead of solving for T using knowledge of A and E, A and E were determined from the steady energy equation using the experimentally determined distribution of T.

A typical measured temperature profile and a corresponding steady state solution obtained theoretically are shown in Fig. 5. The temperature is plotted as a function of the normal distance y from the burner surface. Two factors are of interest; the flame standoff distance is of the order of 1 cm thus enabling experimental probing and the steady state temperature gradient is very small in the neighborhood of $y = 0$. This means that heat transfer (by conduction) to the burner surface is not an important factor in the experiments. It should be noted, however, that this is not true for actual solid propellant flames for which the stand off distance is of the order of 50 microns. The implication of this will be discussed shortly. One should also note the sharp temperature rise in the flame or reaction zone. The corresponding steady state reaction rate profile is shown in Fig. 6.

The value of v' at $y = 0$ was obtained in terms of the acoustic admittance R (i.e., $R = v'/p'$ at $y = 0$) of the side wall burner surface. This admittance was obtained experimentally using the impedance tube technique. The measured admittance[20,21] is plotted as a function of frequency in Fig. 7 and is seen to depend strongly upon it.

To determine the flame driving characteristics, consider first the comparisons of predicted Real (v') distributions with values obtained experimentally using an LDV system. As noted earlier, this gives a quantitative measure of the driving/damping by the flame. In Fig. 8, Real (v') is plotted

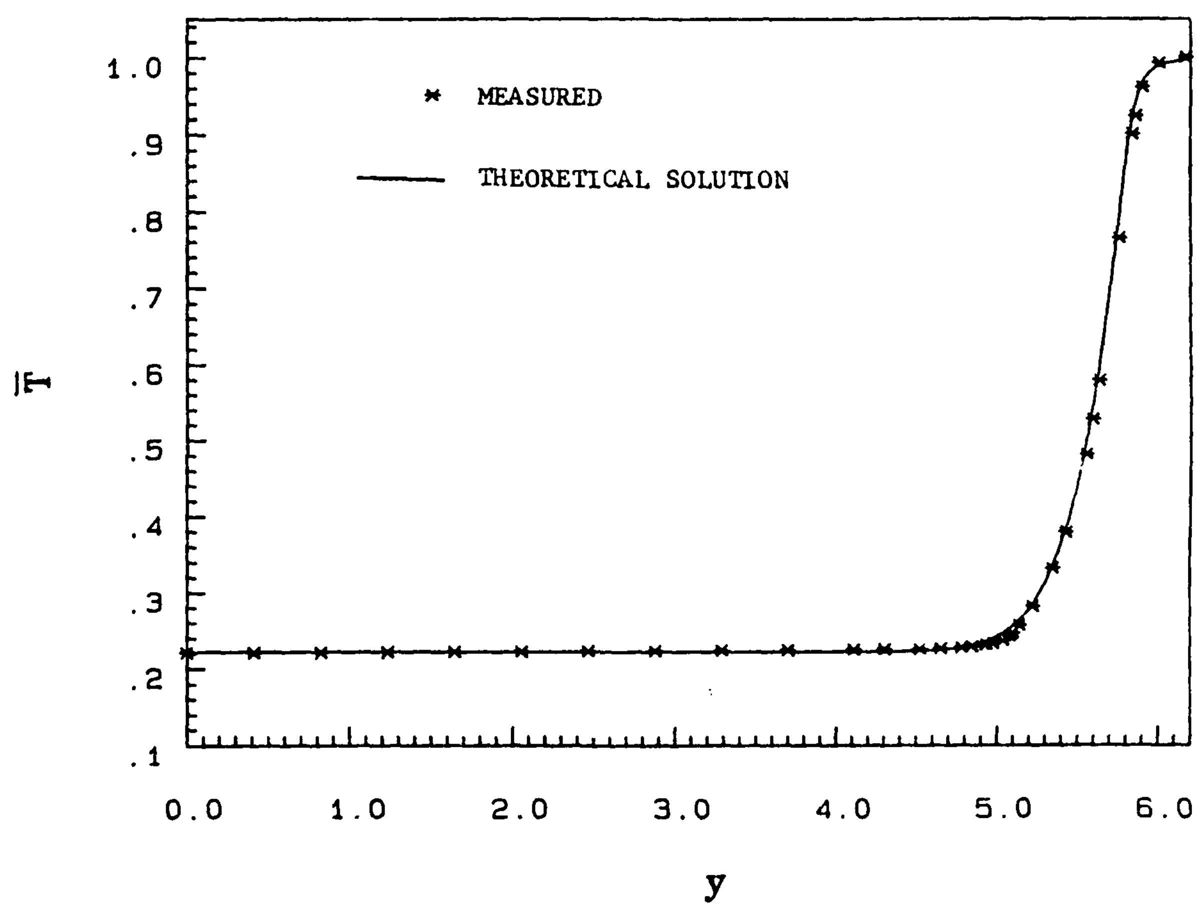


Fig. 5. Typical Temperature Distribution as a Function of the Normal Distance, y (Non-Dimensional), from the Burner Surface.

as a function of y at a frequency of 200 Hz (the driving frequency). At y = 0, it is given by the sidewall admittance and is negative indicating that the sidewall acts as an acoustic damper. It varies slowly between the burner surface (y = 0) and the flame region where the strongest temperature rise occurs (compare with Fig.5). In this flame region Real (v') becomes sharply less negative(or equivalently more positive and more in phase with the pressure oscillations). This means that at 200 Hz, the flame inputs energy into the core flow oscillations. Note also that the prediction of the model (the solid line) agrees extremely well with the measurements. It is also important to note that although the flame inputs energy into the acoustic field (by decreasing the "negativeness" of Real (v')), it is not able to overcome the strong damping effect of the sidewall burner surface. This implies that in a solid rocket motor situation, the admittance at the propellant surface is an important parameter relating to axial instabilities.

Consider next a case where the driving was at 400 Hz (Fig. 9). In this case Real (v') becomes even more negative in the flame region which indicates damping by the flame. What is important here is that the model agrees with the measurements and therefore demonstrates its capability to distinguish between situations where the flame drives or damps.

From the Rayleigh criterion point of view, the phase of the unsteady heat release needs to be compared with that of the pressure. The heat release fluctuations have a component in phase with the pressure oscillations if the phase difference between the two is less than + 90^{o}. The predictions of the model are compared with experimentally measured values of the phase in Fig. 10. These were obtained by measurements of overall CC radiation emission from the flame. As noted in earlier reports,[8,9,20] these emissions are indicative of the heat release rates from the flame. Note that at 200 Hz, p' and q' are

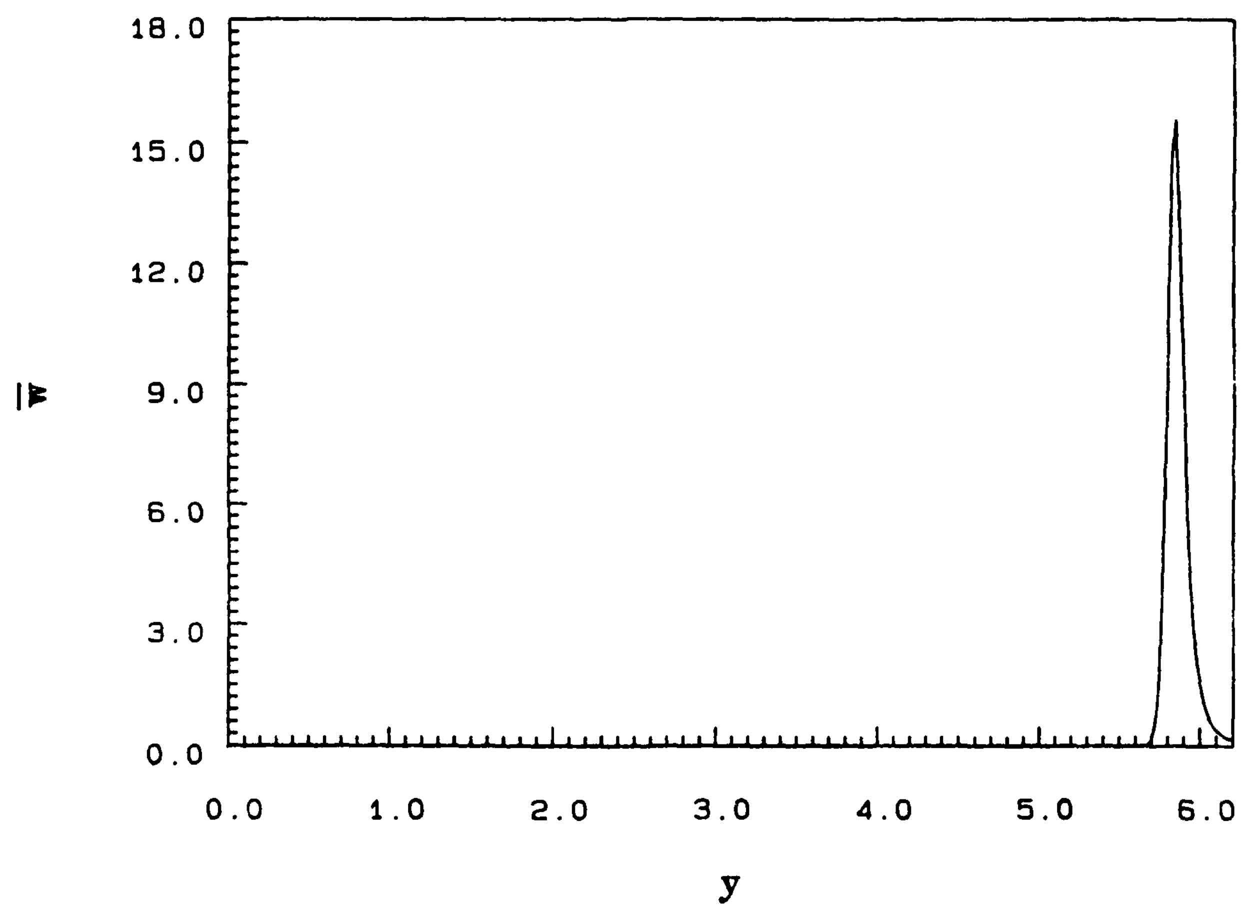


Fig. 6. Steady State Reaction Rate Profile.

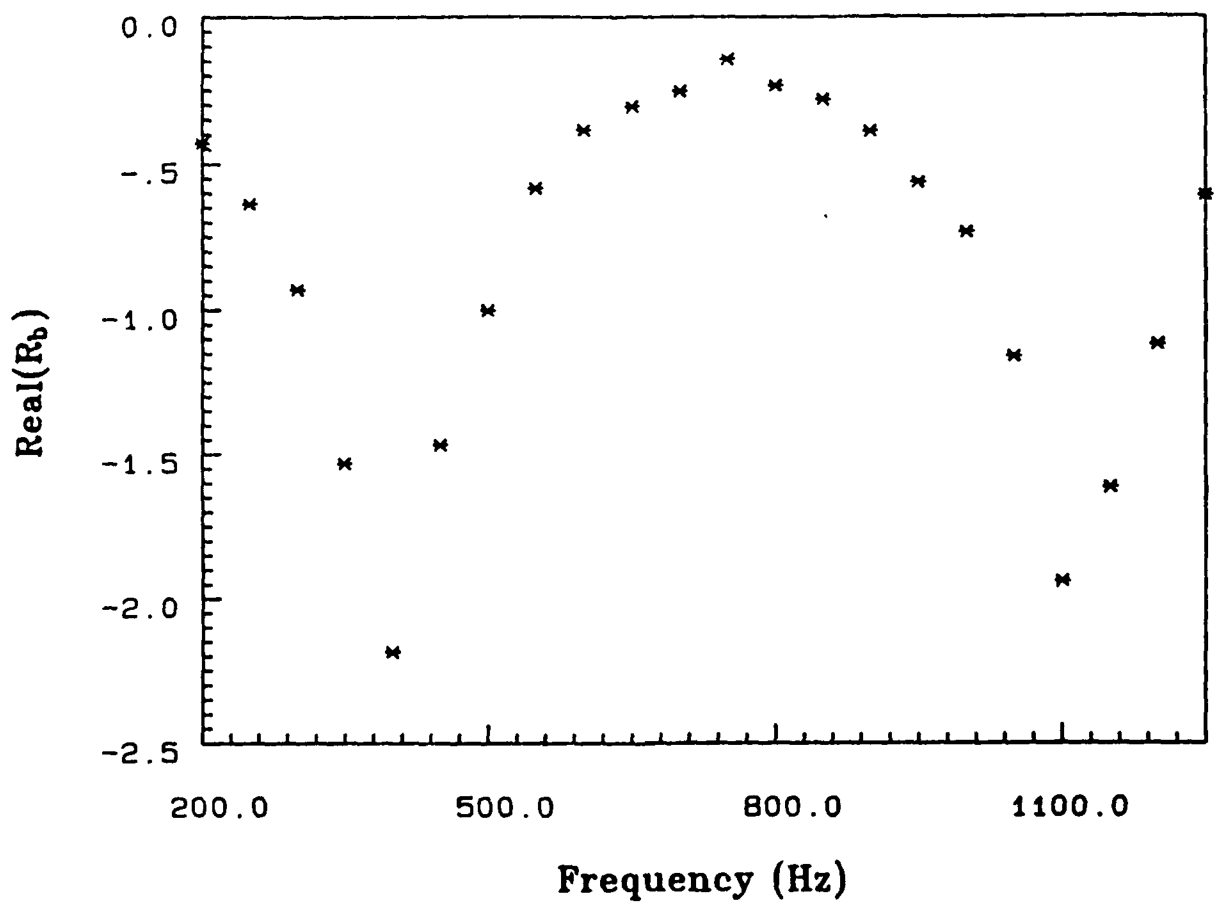


Fig. 7. Measured Real Part of the Burner Surface Admittance as a Function of Frequency.

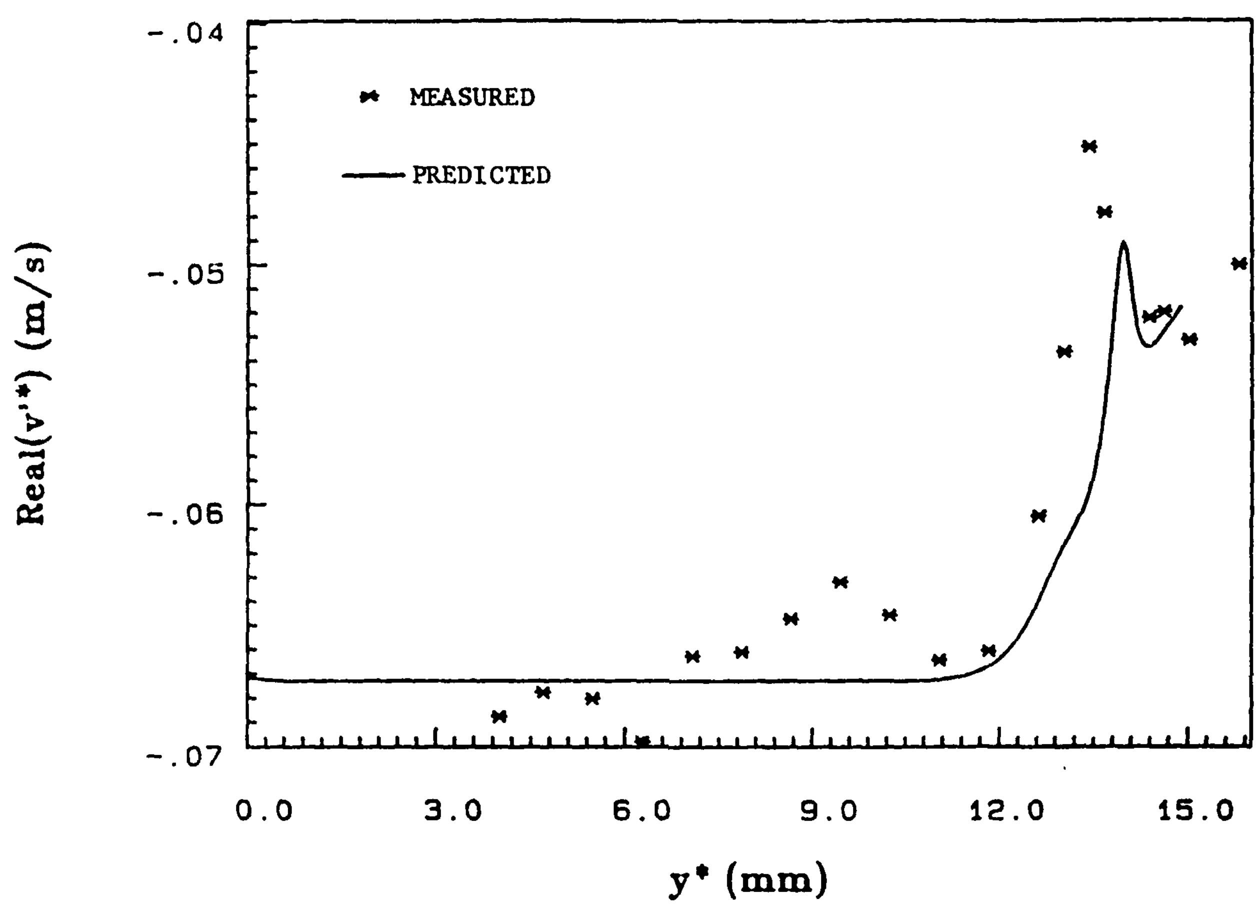


Fig. 8. Measured and Predicted Values of Real (v′) as a Function of the Normal Distance from the Burner Surface at 200 Hz.

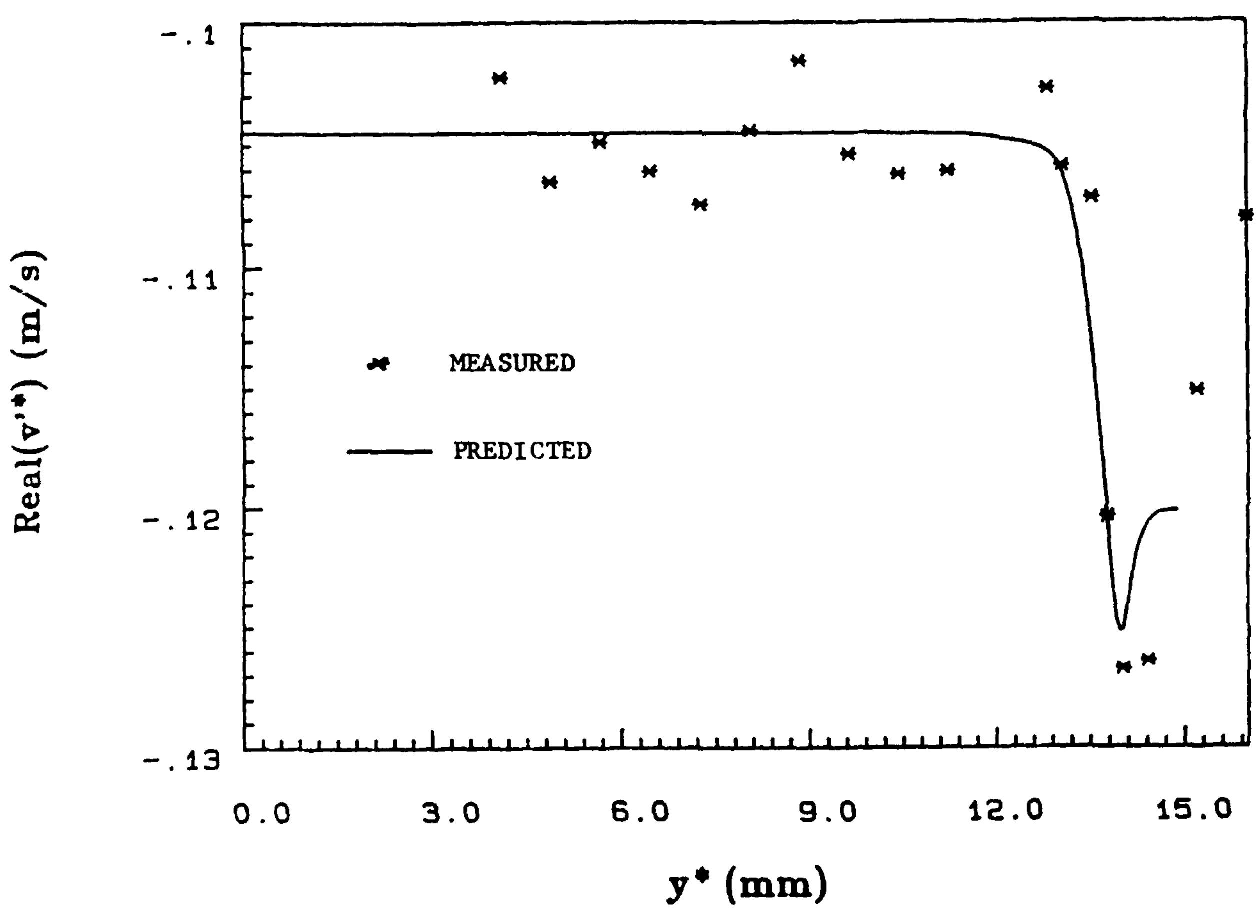


Fig. 9. Measured and Predicted Values of Real (v') as a Function of the Normal Distance from the Burner Surface at 400 Hz.

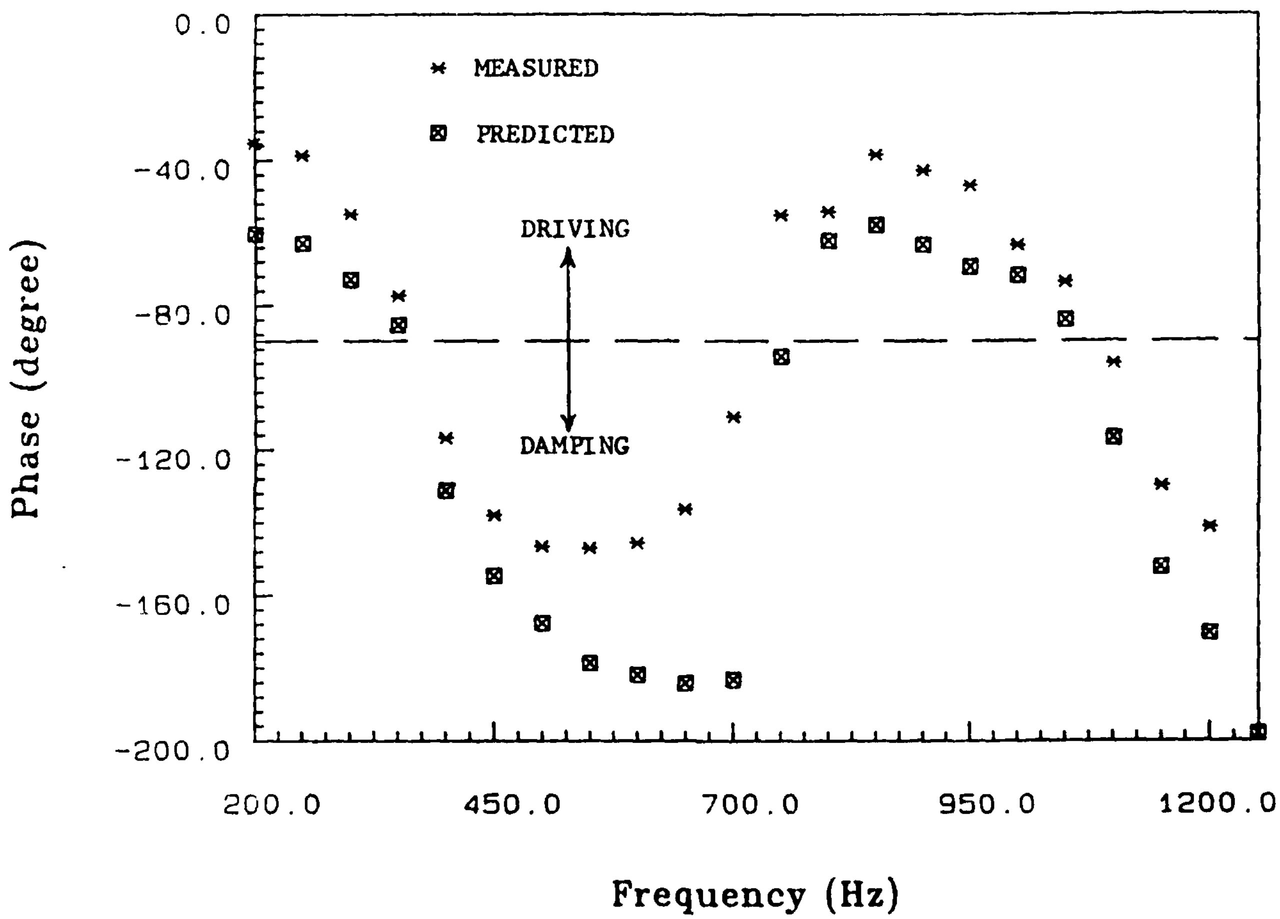


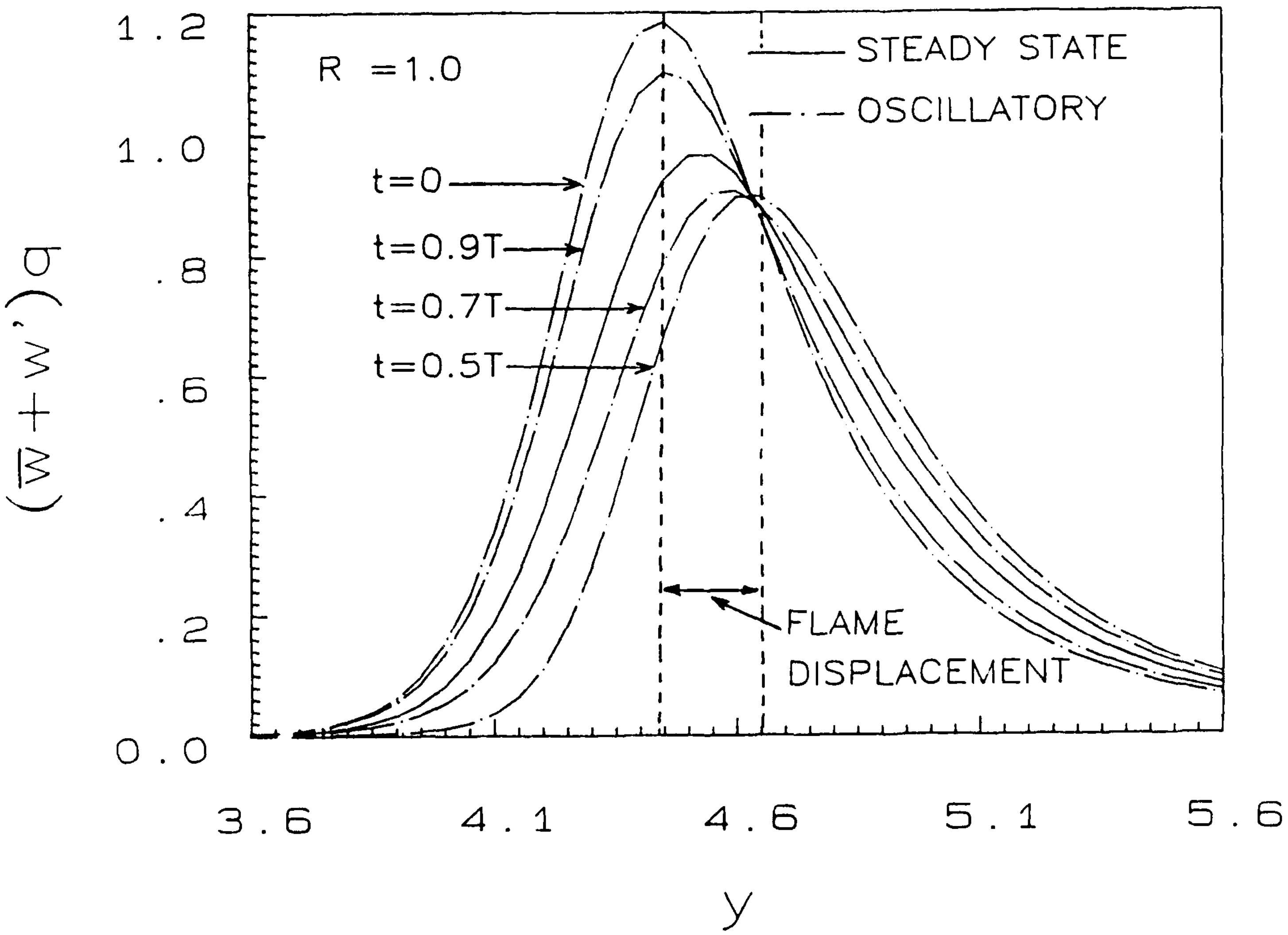
Fig. 10. Measured and Predicted Phase of the Unsteady Heat Release (Radiation) with Respect to the Imposed Pressure Oscillations.

in phase (indicating flame driving of the acoustics) while at 400 Hz they are out of phase (indicating flame damping of the acoustics). These predictions are in agreement with the trends exhibited by Real (v') in Figures 8 and 9. Also, the theoretically predicted trends are in good agreement with the experimental measurements.

These comparisons were made with the flat flame stabilized at a pressure antinode of the excited standing waves. Similar results were obtained with the flame stabilized at other locations of the standing wave as long as this location was not at a pressure node. At a pressure node, depending upon the excitation levels, the flame surface would get distorted by the appearance of spikes or wavelets and in extreme cases the flame would break up and be extinguished. This feature has been described in earlier reports in detail. Only at very low levels of excitation could a stable flame be maintained. However, under these conditions measurements could not be made with any degree of precision. Consequently, efforts have been concentrated on understanding the flame behavior away from a pressure node.

Important discoveries have been made by considering the time dependent motion of the flame. By means of high speed cinematography (described in References 9 and 20), it was determined that under the influence of a sound field flames located away from a pressure node exhibit an up and down motion relative to their steady state location at the frequency of the excited wave. At the phase of maximum pressure, the flame would be located closest to the sidewall and at the phase of minimum pressure it would be located farthest from the sidewall. A prediction of the flame motion obtained using the developed theoretical model is presented in Fig. 11. It plots the instantaneous heat release rate at different times during a cycle of oscillation as a function of the normal distance y from the sidewall. At any given time, the

Fig. 11. Predicted Time Dependent Heat Rates (Normalized). The Location of the Maximum Heat Release Rate at a Given Time, t, Determines the Instantaneous Flame Location.



location of maximum heat release rate may be identified as the flame location. As the pressure was taken to vary as cos $2\pi t/T$, where T is the period of excitation and t is the time, $t = 0$ represents the phase of maximum pressure. As is seen from the figure, at this time the flame is closest to the side wall. One half period later it is farthest away from the wall. Thus, in this respect too, the predictions of the model are in complete agreement with the experimental observations.

Much more can be learned, however, from a closer inspection of Fig. 11. Note that when the flame is closest to the wall, the instantaneous heat release rate is also the highest during the cycle and when it is farthest the instantaneous heat release rate is the lowest. Similar results were obtained experimentally also (see Ref. 9) in complete agreement with the theoretical model. It was noted earlier that in the experiments, heat transfer from the flame to the sidewall was not an important factor due to the flame standoff distance being of the order of 1 cm which resulted in a very low steady state temperature gradient at the wall. In an actual solid propellant flame standoff distances are, however, of the order of 50-100 microns so that heat transfer to the surface of the propellant is an important issue. If the heat release rate is highest when the flame approaches the propellant surface, as is the case with the premixed flame, a mechanism is available to sustain a non steady burn rate of the propellant in tandem with the pressure oscillations which may lead to strong instabilities.

The Flame Driving Mechanism

Up to this point the discussion has centered upon the excellent agreement between the developed model and the experimental data which indicates

that state of the art models of unsteady solid propellant flames may indeed be capable of capturing the salient features of the flame behavior. Now attention is focused on the driving characteristics (i.e., consideration of the flame as an acoustic source) of the investigated premixed flames. It is well known that the most fundamental acoustic source is a monopole[22] which may be envisioned as a periodically expanding and contracting balloon. Other acoustic sources are obtained by suitable combination of monopole sources; that is, two closely spaced monopoles of equal strength operating 180^o out of phase constitute a dipole[22] and two closely spaced dipoles of equal strength operating 180^o out of phase with each other constitute a quadrupole.

The sharp changes in Real (v') in the flame region (see Figures 8 and 9) indicate a monopole type of acoustic source. The periodic expansion of the gases as they move through the flame under the influence of an acoustic field is similar to, in notion, to that of a periodically expanding and contracting balloon. If this periodic expansion and contraction of the gases is in phase with the pressure oscillations then the resulting pumping action feeds energy into the acoustic oscillations. If the periodic expansion and contraction is out of phase with the acoustic oscillations energy is lost from the acoustic motions.

However, from considerations of the spatial distribution of the heat release rate fluctuations it was found that this picture was not complete. Experimentally, the heat release rate fluctuations may be obtained in terms of emitted CH or CC radiation from the flame (see Ref. 9). These radiation emissions were measured as a function of y by capturing the radiation from narrow(2 mm wide) slits aligned perpendicular to the normal coordinate y by means of a photomultiplier arrangement. As expected, close to the sidewall,

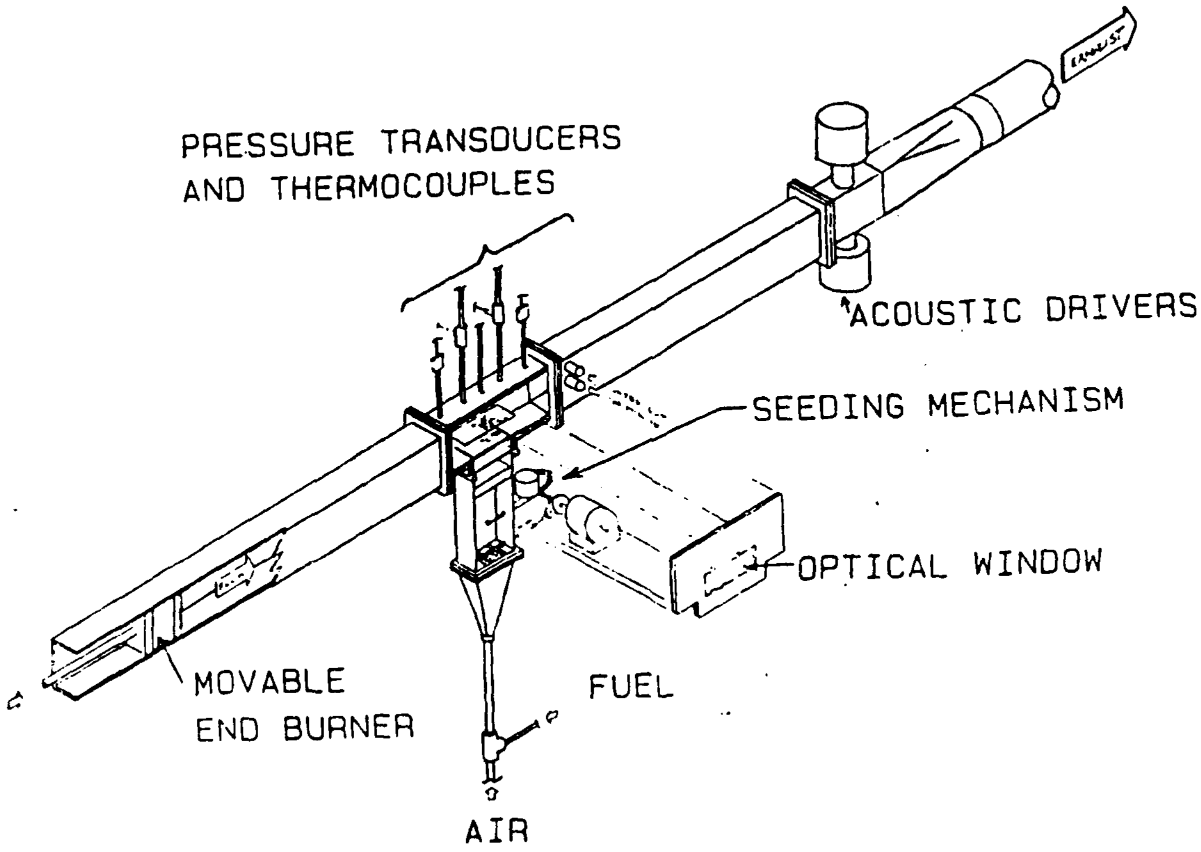


Fig. 3. Developed Experimental Set-Up

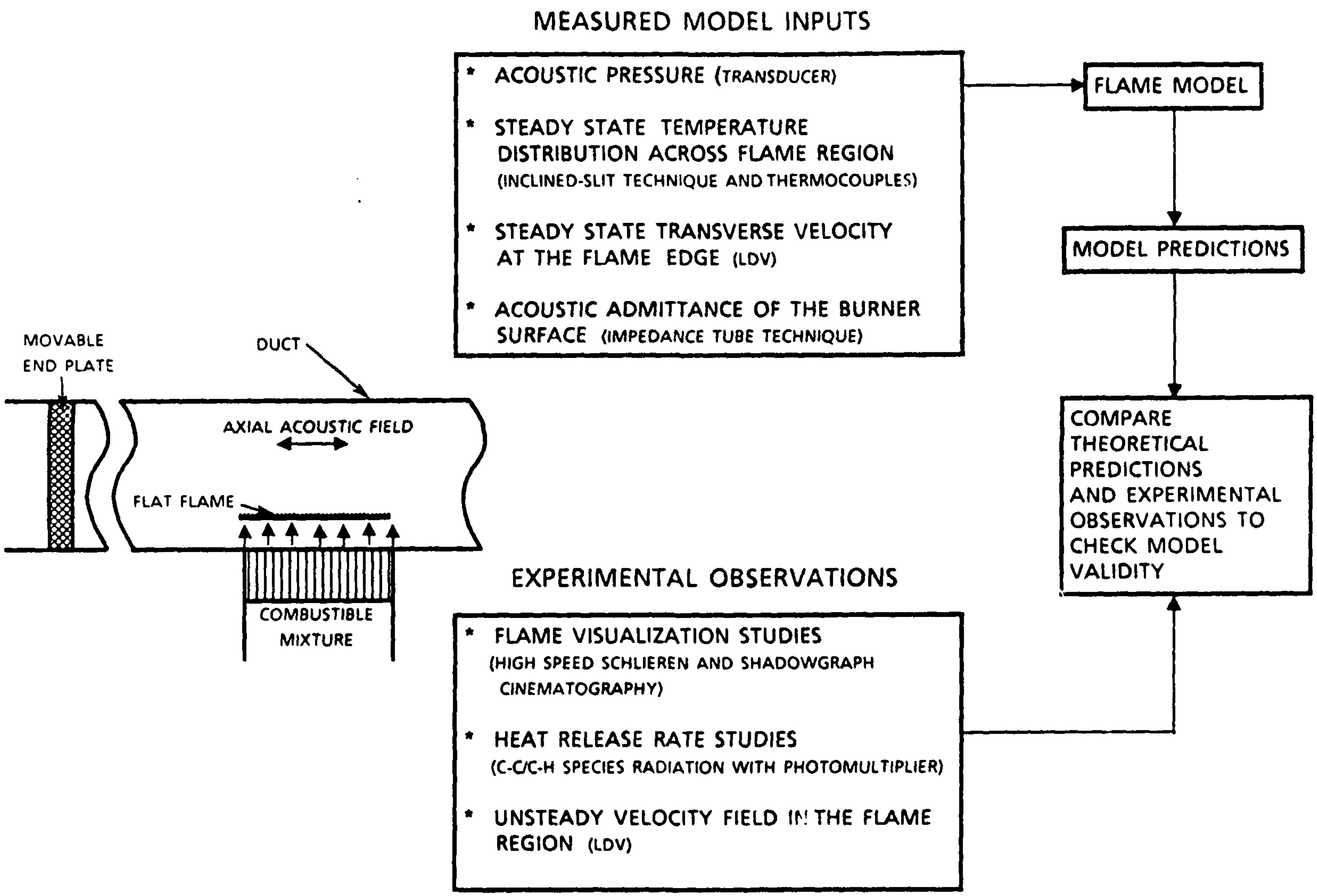


Fig. 4. Summary of the Research Program on the Interaction between Premixed Flat Flames and Longitudinal Acoustical Waves.

the measurements captured only the shot noise from the photomultiplier indicating no significant heat release rates in this region.

The interesting discoveries were made in the vicinity of the steady flame location. Just upstream of this location, a large peak in the magnitude of the unsteady heat release rate was obtained. At the location of the steady flame hardly any unsteady radiation could be detected which at first glance may seem surprising but is not so as will be explained shortly. Just downstream of this location, however, the radiation levels peaked again although the peak was smaller than the first observed peak just upstream of the steady flame location. This behavior was found to occur at frequencies up to 1000 Hz. When the theoretical model was applied to obtain the magnitude of the unsteady heat release rates as a function of y, it showed identical results. An example is shown in Fig. 12, which plots the theoretical radiation levels (normalized) as a function of y for an arbitrary driving frequency. The corresponding experimental result is shown in Fig. 13.

In addition, the model predicted that for all frequencies the heat release rate fluctuations upstream and downstream of the steady flame location differed in phase by 180^o (Fig. 14). According to Rayleigh's criterion the heat release rates may be considered as the acoustic source of the flame. These peaks on either side of the steady flame location are, according to the model, 180^o out of phase with each other. If the magnitude of the upstream peak is thought of as the sum of two parts, one of magnitude equal to the downstream peak and the other accounting for the remainder, then theoretically the flame may be viewed as a combination of an acoustic dipole and a monopole. This result is entirely new and to the best of the investigators knowledge, not found in the literature. This split is important from the point of view of the directionality of the sound emitted by the flame. While

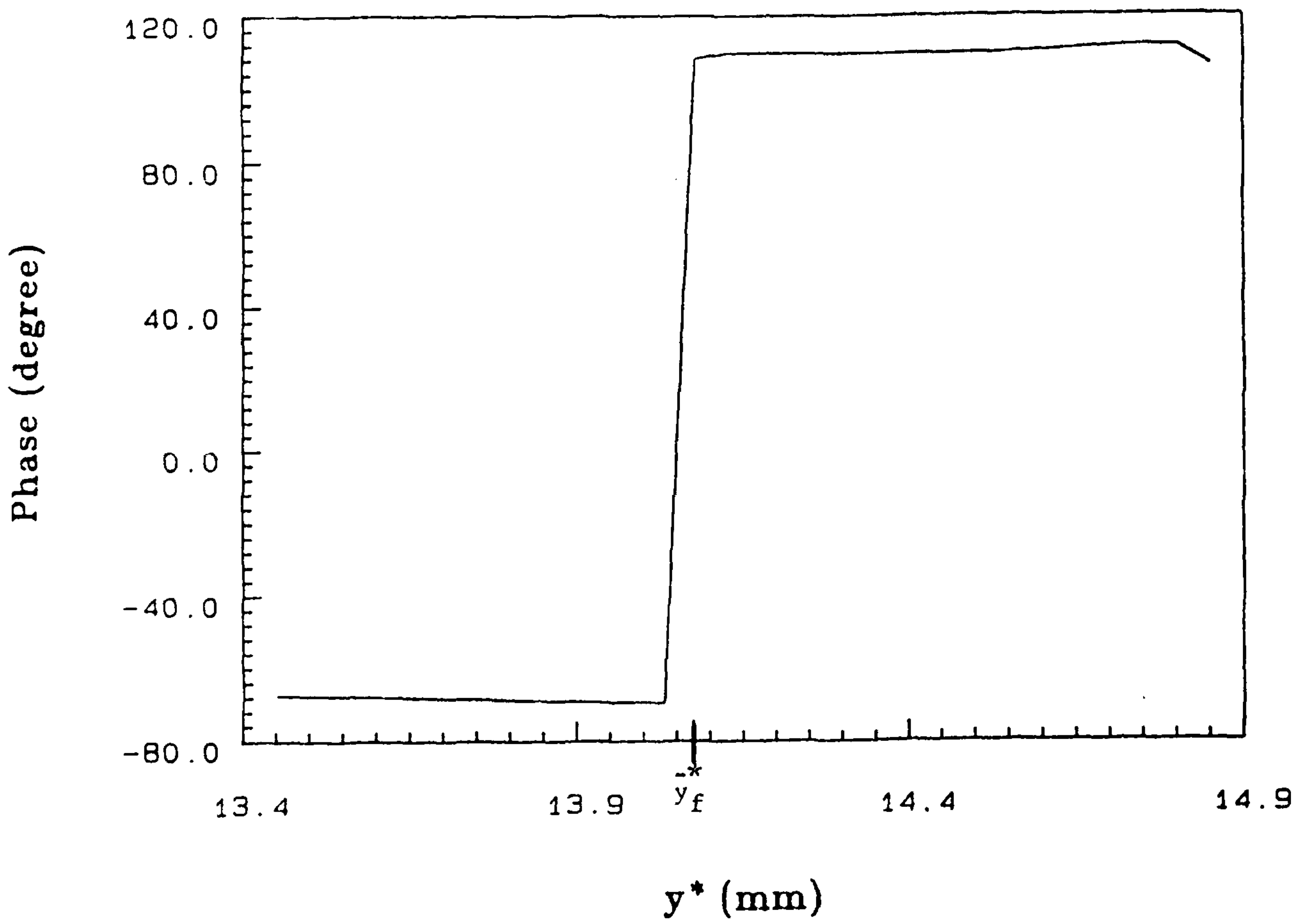


Fig. 14. Predicted Values of the Phase of the Unsteady Heat Release Rate (Radiation) with Respect to the Imposed Pressure Oscillation.

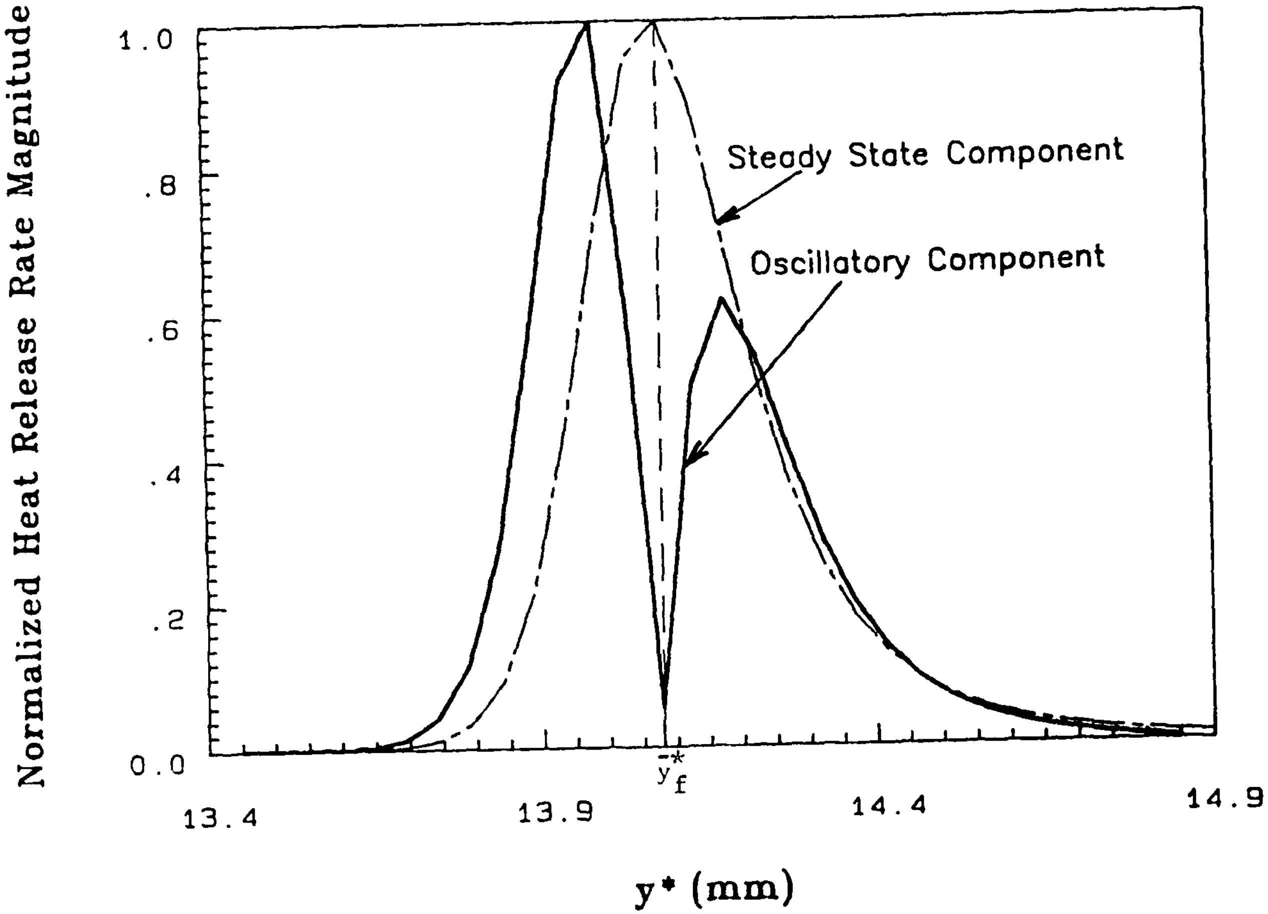


Fig. 12. Predicted Steady State and Oscillatory Heat Release Rate Magnitudes. Note the Sharp Peaks of the Oscillatory Component Upstream and Downstream of the Steady State Flame Location ($\bar{y}_f^*$).

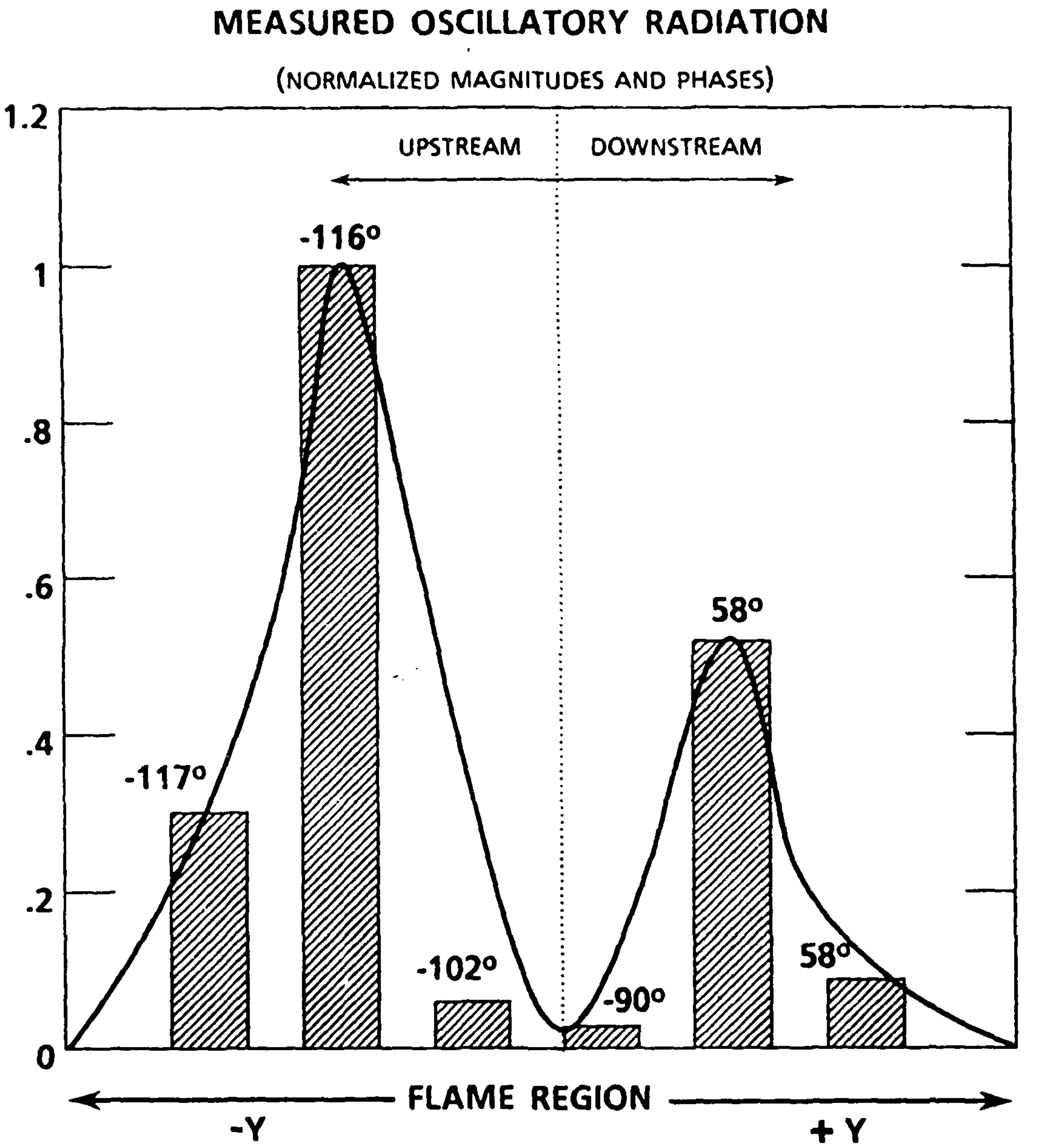


Fig. 13. Measured Oscillatory Radiation (Heat Release Rate) in the Flame Region.

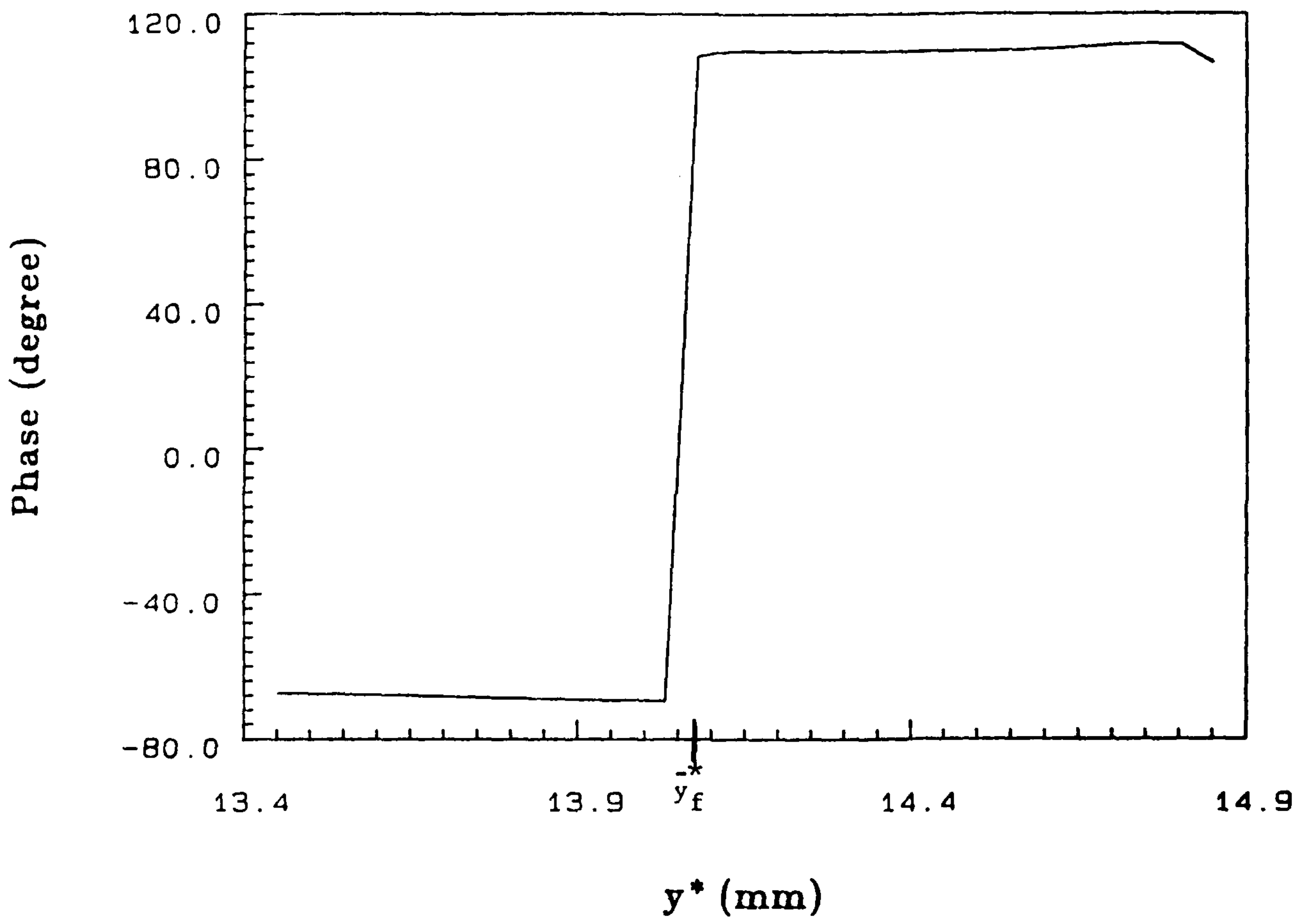


Fig. 14. Predicted Values of the Phase of the Unsteady Heat Release Rate (Radiation) with Respect to the Imposed Pressure Oscillation.

a monopole source is non directional in nature, a dipole source shows a strong preference for channeling the emitted sound waves along its axis(determined by joining the centers of the two monopoles constituting the dipole). Thus, for a ducted flame, the monopole source will exhibit a directional preference purely due to wave guide effects created by the confining effects of the duct walls[22] while the dipole source introduces additional directionality of its own. This may become important if transverse acoustic modes are considered.

The only discrepancy between the theoretical model and the experimental measurements was found in the phase difference between the radiation (heat release rate fluctuation) peaks upstream and downstream of the flame. Experimentally, it was found that the phase difference was not always 180° but varied between 130° to $180.^{\circ}$ This may not be, however, entirely the model's fault as the spatial resolution of the radiation measurements was limited by data acquisition constraints. A set of experimentally obtained phase values is also presented in Fig. 13.

The reason why the radiation fluctuations at the steady state flame location are small in comparison to the sharp peaks obtained upstream and downstream (Figures 12 and 13) remains to be discussed. This may be understood by considering Fig. 11. At any location y, the magnitude of the radiation fluctuations is equal to the difference in the values of the levels at t = 0 and t = 0.5T. Upstream and downstream of the steady flame location (situated in the flame displacement zone) this difference is seen to be high with the upstream levels being of greater magnitude. This corresponds to the two peaks noted earlier. However, in the region close to the steady state flame location, the curves of the instantaneous heat release rates at all times during a cycle of oscillation intersect. This indicates very weak

fluctuations in the reaction rate at this location and explains the low radiation fluctuation levels obtained here.

Summary

Keeping in mind the previously stated objectives of Task I of the research program the following conclusions may be drawn:

(i) The close agreement between theory and experiment indicates that state of the art models of unsteady solid propellant flames are indeed capable of predicting the flame acoustic interactions during axial instabilities.

(ii) The effect of the flame driving or damping characteristics is manifested in sharp changes in the normal velocity fluctuations in the flame region. These normal velocity oscillations are equivalent to a piston which supplies or receives acoustic energy from the core flow oscillations.

(iii) Unsteady heat transfer from the flame to the propellant surface may provide a feedback mechanism between the propellant burn rate and acoustic oscillations which supplies the energy needed to sustain axial instabilities.

(iv) The acoustic admittance at the propellant surface may exert considerable influence upon the overall driving/damping characteristics of the rocket motor.

(v) The flame may be considered as a combination of an acoustic monopole and an acoustic dipole. The dipole nature may become important in studies of transverse wave mode instabilities

Task II

Interaction of Side Wall Stabilized Diffusion Flames with Axial Acoustic Fields

Task II of this research program investigated the role of diffusion limited processes upon the driving/damping of axial instabilities in solid propellant rocket motors. The major objectives of this task were:

1. To incorporate the effect of diffusion processes in theoretical models unsteady solid propellant flames and
2. To investigate the influence of diffusion processes in the flame region on the acoustic driving/damping characteristics of the flame.

The utilized experimental setup is described first. This is followed by a discussion of the conducted theoretical and experimental investigations.

Experimental Setup

A schematic of the developed experimental set up is shown in Fig. 15. It consists of a long rectangular tube having a diffusion flame burner on one of its side walls, an axially movable injector plate at the inlet end and two phase locked acoustic drivers at the exhaust end. During an experiment, diffusion flames are stabilized on the lower burner surface. Next, the acoustic drivers are turned on to excite a standing longitudinal acoustic wave of desired frequency and amplitude in the duct. The latter simulates the axial oscillations observed in unstable solid propellant rocket motors.

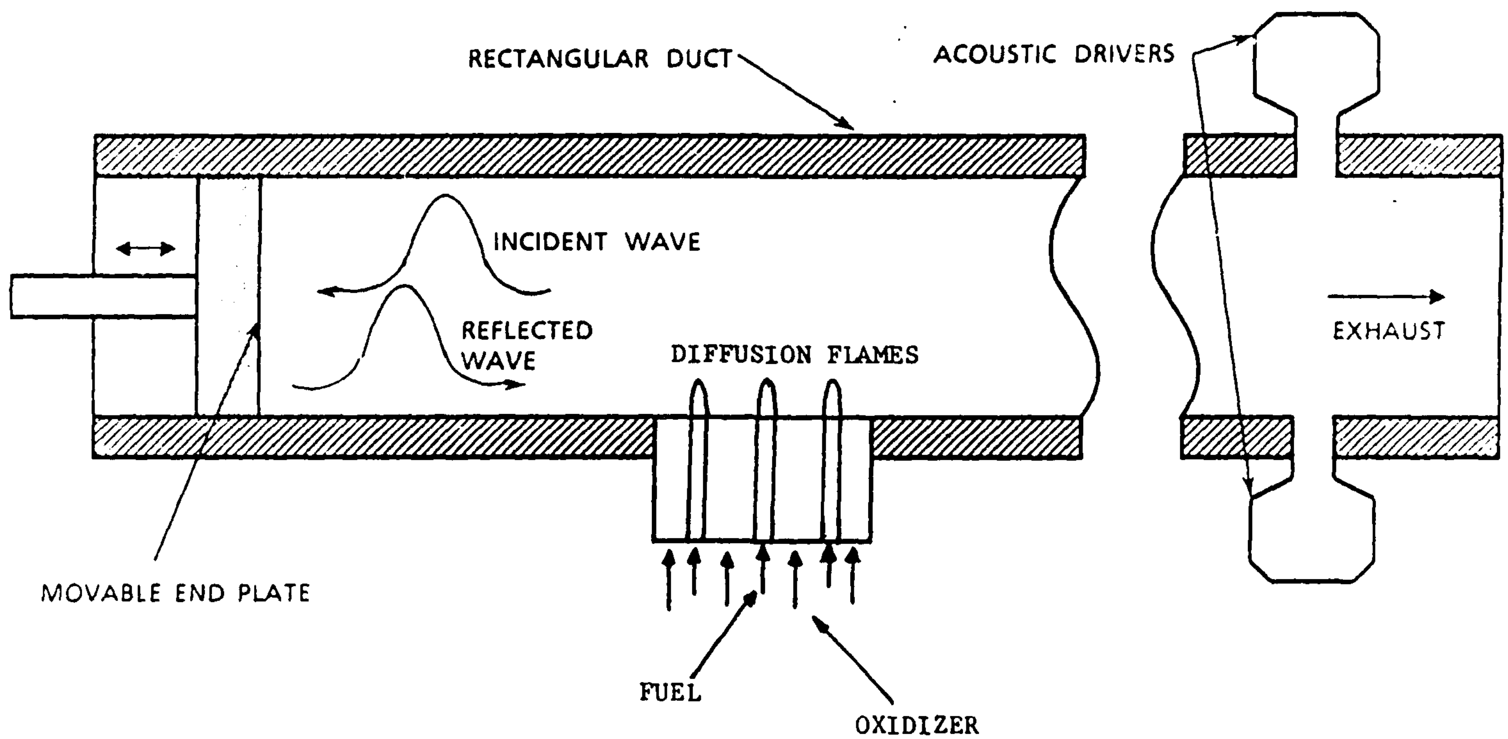


Fig. 15 Schematic of the Proposed Experimental Set-Up to Investigate the Interactions between Gas Phase Diffusion Flames and Longitudinal Acoustic Fields.

The position of the burner and, consequently the positions of the flames relative to the standing acoustic wave (i.e., next to a pressure node or pressure antinode) can be varied by moving the injector plate axially.

The diffusion flame burner utilized during the studies conducted during the past year is shown in Fig. 16. Fuel (propane) and air are injected through alternate slots and this results in three diffusion flames being established at the burner surface. This type of burner has two advantages. First, the resulting diffusion flame configuration is geometrically simple and, therefore, amenable to theoretical analysis. Secondly, the developed diffusion flames are similar to the sandwich type of propellant flames with alternating oxidizer and binder sections (see Fig. 2) which have been utilized in the past to study solid propellant combustion[12].

Theoretical Investigations

One of the objectives of the diffusion flame studies is the development of a theoretical model of oscillatory diffusion flames stabilized in longitudinal sound fields simulating those found in unstable solid propellant rocket motors. Such a model, based upon the Schvab-Zeldovich coupling function formalism[11], has been developed during this program. This approach was adopted as it is known to be capable of predicting the behavior of diffusion flames under steady conditions. Moreover, it captures the effects of diffusion processes which are the focus of this phase of the investigation.

The Schvab-Zeldovich approach is most applicable to those cases in which the diffusion rates of fuel and oxidizer towards each other control the overall reaction rates; that is, cases where the chemical reaction time is very much smaller that the time required for the diffusion of the reactants

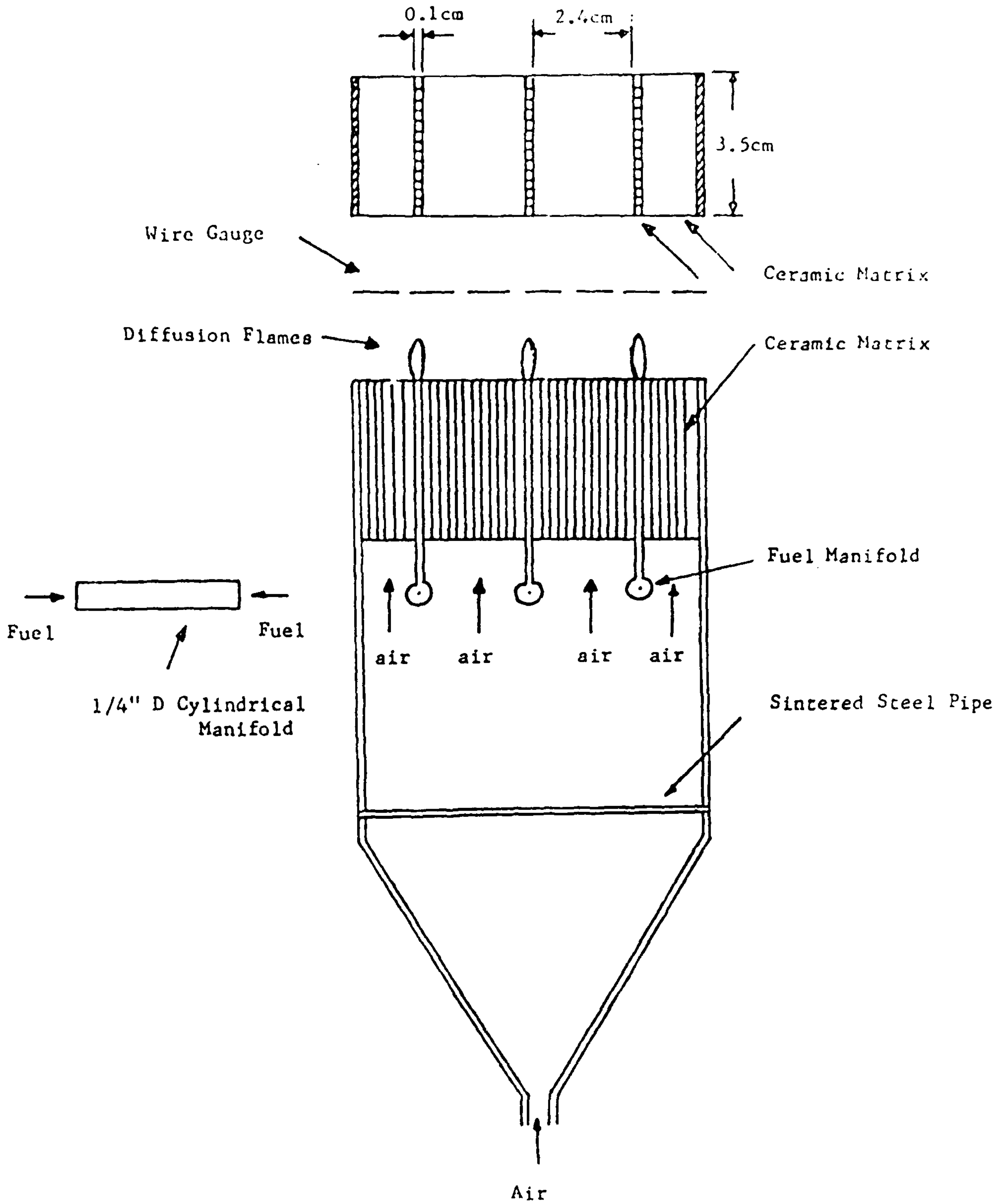


Fig 16. Developed Diffusion Flame Burner.

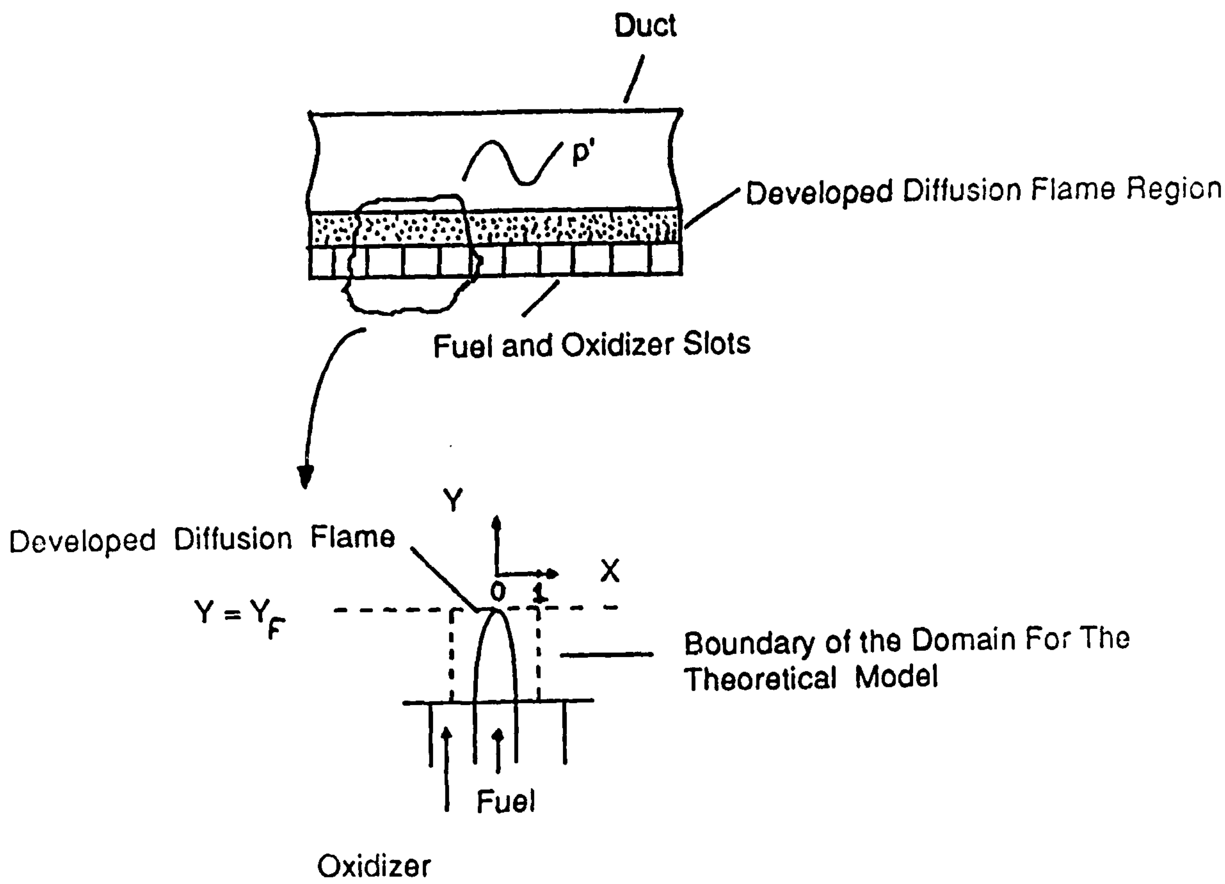


Fig. 17 Configuration for the Theoretical Model of the Diffusion Flame Acoustic Interactions.

towards each other. In such cases, the actual flame region may be taken to lie on a surface or sheet. Moreover, by appropriate definitions of temperature and species coupling functions, β^T and β, respectively, the chemical reaction rates may be eliminated from consideration.

The *theoretical model* considers the configuration shown in Fig. 17. A number of diffusion flames are established on the side wall of a duct by means of alternate fuel and oxidizer slots. This configuration is similar to the experimental set up considered in Figs. 15 and 16. These flames are exposed to known axial acoustic pressure and velocity oscillations. Of interest is the response of these flames to the imposed oscillations. It is sufficient to consider a single flame as the response of any one of the flames is largely governed by the conditions existing locally. Thus, the model considers the single diffusion flame shown in Fig. 17. The influence of the other flames is accommodated by prescribing the flow variables along the boundary of the domain of interest as shown in Fig. 17.

The model considers three unknowns; namely, (1) the normal velocity fluctuation v' (2) the fluctuations in the temperature coupling function β'_T, and (3) the fluctuations in the species coupling function, β'.

These unknowns are related to the applied acoustic field described in terms of known pressure fluctuations, p', and axial velocity fluctuations, u', by making use of the conservation equations for mass, momentun and energy along with the equation of state. A matrix equation of the following form emerges:

$$A_{ij}\nabla^2 X_i + B_{ij}\nabla \bullet X_i + C_{ij} X_i = F_i$$

where

$$X_i = (v', \beta'_T, \beta')^T$$

and A_{ij}, B_{ij} and C_{ij} are 3 x 3 coefficient matrices which depend upon the steady state solutions. These have to be obtained experimentally or by a combination of theory and experiment. F_i depends upon p' and u' as well as upon the steady state solutions and may be regarded as a forcing function for the unknowns X_i. Conditions on the velocity, temperature and species fractions (i.e., on v', β'_T and β') have to be prescribed on the boundary as depicted in Fig. 7. These boundary conditions have to be obtained experimentally for a general case. However, these conditions may be specified approximately as follows:

(a) At the burner surface (i.e, y=0) the fuel and oxidizer streams are each honmogeneous and separate from one another so that there are no fluctuations in the species fractions at this location. Moreover, temperature fluctuations at the ceramic matrix surface of the burner are expected to be negligible. This implies that at y=0, $\beta'_T = 0$ and $\beta' = 0$. The condition on v' at y=0 is specified in terms of the acoustic admittance R of the burner surface; that is,

$$v'(y=0) = Rp'$$

(b) At x=0 and at x=1, conditions may be expected to be symmetric if one considers the middle diffusion flame (which has similar diffusion flames on either side.) Hence, the conditions may be specified to be

$$\partial\beta_T / \partial x = 0 \qquad \text{and} \qquad \partial\beta' / \partial x = 0 \qquad \text{at } x=0 \text{ and at } x=1$$

A computer program for solving the model equations has been developed. A Crank-Nicholson implicit numerical scheme which employs uniform grid spacings in both the x and y directions is utilized to obtain a finite difference representation of the developed matrix equation. A block tridiagonal system of finite difference equations is formed at each

y-location which can be inverted efficiently using standard algorithms to obtain the required unsteady solutions.

Results obtained using a hypothetical set of input and forcing conditions are shown in Figs. 18 and 19. For this case, the burner surface admittance has been taken to be purely reactive; that is, the real part of v' (the component in phase with p') at the burner surface is zero and v' leads p' by 90^{o} at the surface. Figure 18 describes the variation of the magnitude of v' at the top edge of the flame (i.e., at $y = y_f$) as a function of x (see Fig. 17)> Figure 19 describes the variations of the phase of v' with respect to p' at this location (i.e., $y=y_f$) as a function of x. These results show that for the assumed conditions the magnitude of v' exhibits a maximum in the vicinity of the flame surface. Figure 19 also shows that the phase difference between p' and v' is less than 90^{o} in this region. This indicates the presence of a positive real part of v' (i.e., the component in phase with p'). As shown previously, the product of the in-phase components of p' and v' yields the energy input into the acoustic wave by the flame in the vicinity of the flame surface. A smaller peak in the magnitude of v' appears a short distance axially downstream of the flame surface. Significantly, in this region (see Fig. 19), p' and v' are out of phase indicating a damping of the acoustic motions and the presence of a negative real part of v' in this region.

Thus, the model predicts the occurrence of driving and damping regions within the flame. This is similar to the monopole-dipole mechanism occurring in the premixed flame case which was investigated during Phase I of this program. This similarity suggests that the developed diffusion flame model may indeed be capable of predicting the driving characteristics of diffusion flames.

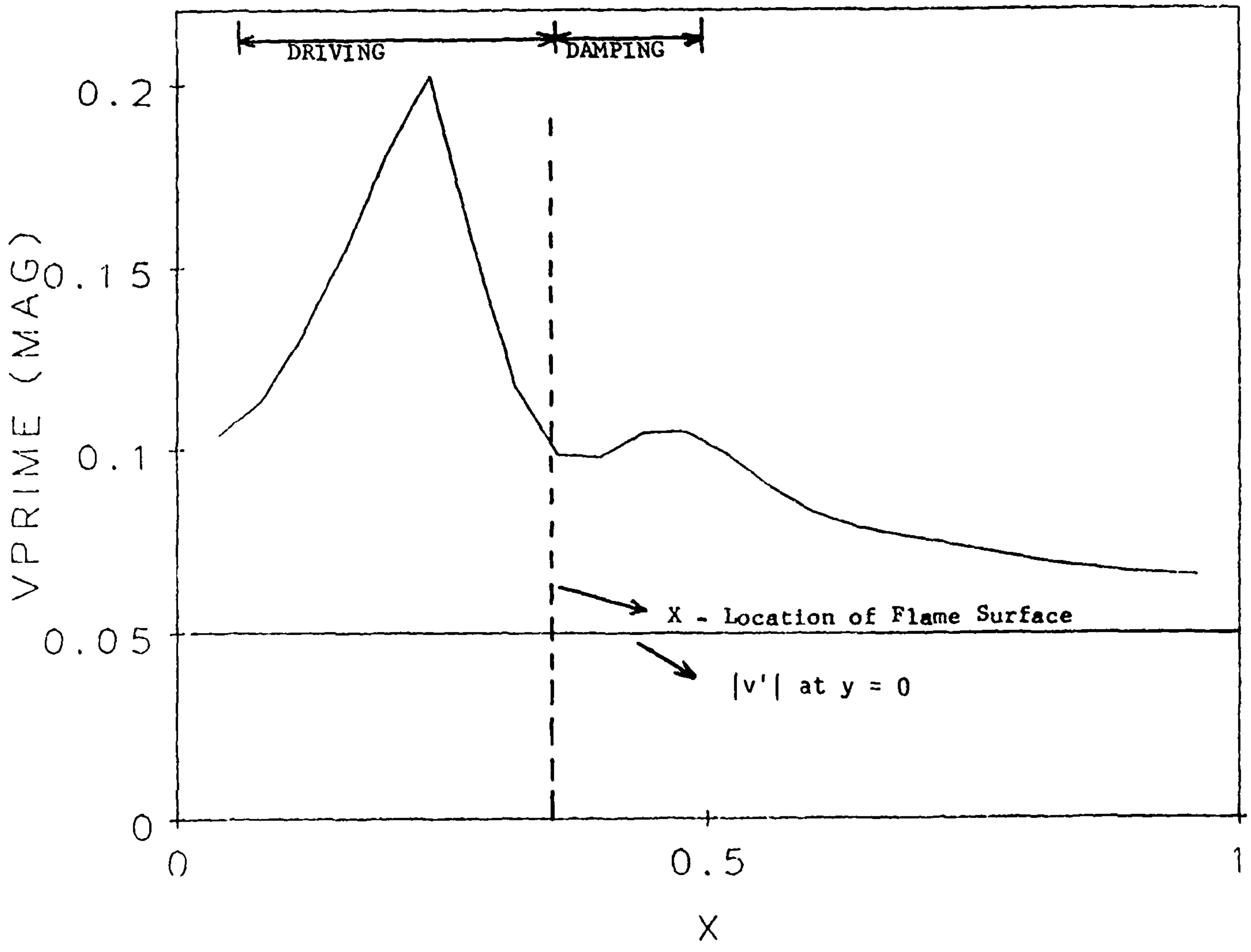


Fig. 18 Computed $|v'|$ at $y = y_f$ as a function of x.

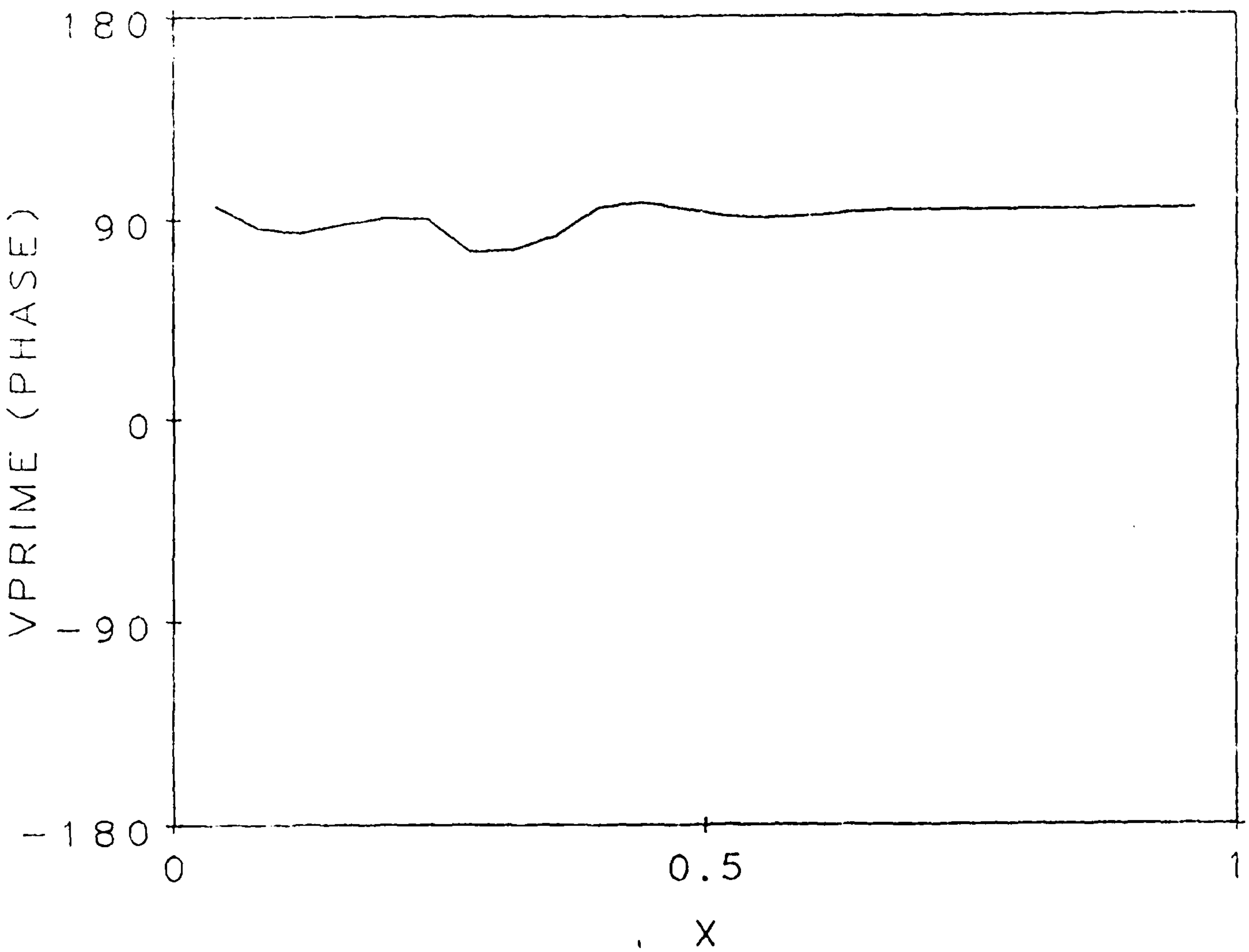


Fig. 19 Computed phase of v' at $y = y_f$ as a function of x.

Experimental Efforts

The experimental studies conducted to date included high speed flame shadowgraphy visualizations and measurements of CH radiation from the flame.

High speed shadowgraph films (5000 frames/sec) have been taken with the flame excited at different frequencies in the 250 - 1000 Hz. range by means of the acoustic drivers (see Fig. 15). The axially movable end plate made it possible to place the diffusion flame burner on different locations of the established standing wave; that is, at a pressure maximum, minimum or in between. Analyses of the films indicate that under the influence of an acoustic field the flame oscillates axially and the frequency of oscillation coincides with the frequency of the excited acoustic wave.

Measurements of C-H radiation emitted by the diffusion flames have also been carried out for different frequencies and flame locations as noted above. These measurements are indicative of the heat release rates of the flames. An example of the measured phase difference between the flame radiation and acoustic pressure oscillations at a pressure maximum for different frequencies in the 250 to 1000 Hz. range is shown in Fig. 20. According to Rayleigh's criterion, when the phase difference between the two is less than 90^o the flame drives the acoustic field. Thus, it may be noted that depending upon the frequency, the flame may either drive or damp the acoustic oscillations.

Due to time constraints, the validity of the developed theoretical model could not be completely assessed during the period of this grant. However, its validity will be ascertained under an extension of this program in which the major focus will shift to the importance of flow turning phenomena in damping and driving axial instabilities. The model will be checked by

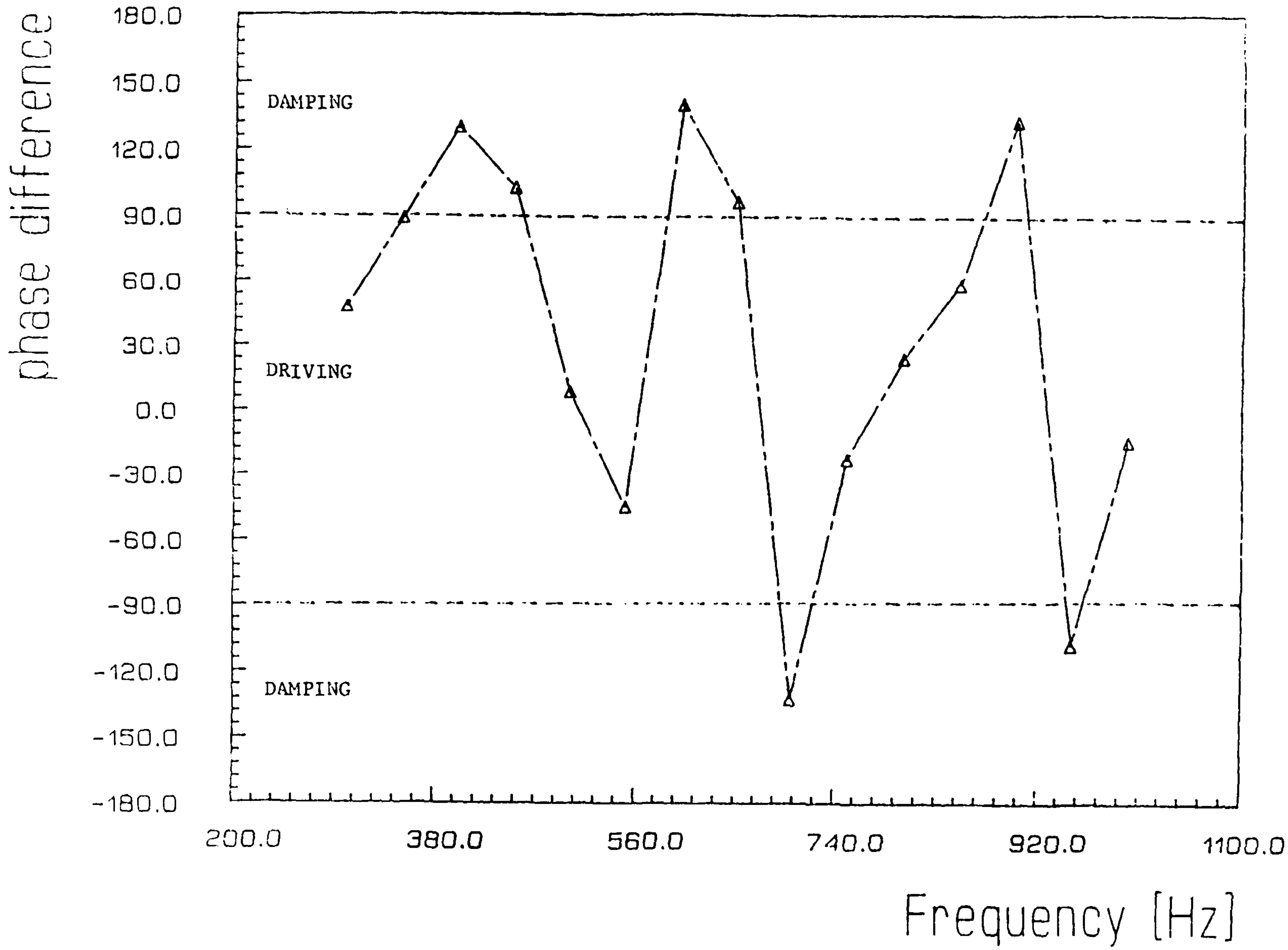


Fig. 20 Frequency Dependence of the Phase Difference Between the Flame Radiation and Acoustic Pressure Oscillations Measured with the Flame at a Pressure Maximum.

comparing the distribution of the unsteady velocity v' measured using an LDV with the theoretical predictions. Measurements of the steady state temperature distributions in the flame region and the acoustic admittance of the ceramic burner surface will also be needed as inputs to the theoretical model.

Summary

The studies conducted under Task II of the program have shown:

(i) Side wall stabilized diffusion flames are responsive to axial acoustic oscillations

(ii) The acoustic driving/damping characteristics of diffusion flames are frequency dependent.

(iii) The acoustic nature of diffusion flames is similar to the monopole-dipole characteristics of premixed flames.

(iv) Diffusion processes may be incorporated into theoretical models which describe unsteady solid propellant flame behavior.

REFERENCES

1. Price, E. W. and Culick, F. E. C., "Combustion of Solid Rocket Propellants," AIAA Professional Study Series.
2. Cohen, N. S., "Review of Composite Propellant Burn Rate Modelling," AIAA Journal, Vol. 18, pp. 277-293, March 1980.
3. Denison, M. R. and Baum, E., "A Simplified Model of Unstable Burning in Solid Propellants," ARS Journal, Vol. 31, No. 8, pp. 1112-1122, Aug. 1961.
4. Culick, F. E. C., "A Review of Calculations for Unsteady Burning of a Solid Propellant," AIAA Journal, Vol. 6, No. 12, pp. 2241-2256, Dec. 1968.
5. Williams, F. A. and Lengelle, G., "Simplified Model for Effect of Solid Heterogeneity on Oscillatory Combustion," Astronautica Acta, Vol. 14, pp. 97-118, Jan. 1968.
6. Flandro, G. A., "Nonlinear Time Dependent Combustion of a Solid Rocket Propellant," CPIA Publication No. 366, Vol. II, pp. 111-122, Oct. 1982.
7. Cohen, N. S. and Strand, L. D., "Combustion Response to Compositional Fluctuations," AIAA Paper No. 83-0476.
8. Zinn, B. T. and Daniel, B. R., "Investigation of the Flame-Acoustic Wave Interaction during Axial Solid Rocket Instabilities," Proposal submitted to AFOSR in Sept. 1984.
9. Zinn, B. T. and Daniel, B. R., "Investigation of the Flame-Acoustic Wave Interaction During Axial Solid Rocket Instabilities," Proposal submitted to AFOSR in Oct. 1985.

10. Hegde, U. G. and Zinn, B. T., "The Acoustic Boundary Layer in Porous Walled Ducts with a Reacting Flow," Proceedings of the Twenty-First (International) Symposium on Combustion, Aug. 1986.

11. Williams, F. A., "Combustion Theory," Second Edition, Benjamin/Cummings, California, 1985.

12. Price, E. W. and Sambamurthi, J. K., "Dependence of Burning Rate of AP-Polymer Sandwiches on Thickness of the Binder Laminae," Proceedings of the 20th JANNAF Combustion Meeting, Oct. 1983.

13. Friedman, R., "Measurement of the Temperature Profile in a Laminar Flame," Fourth Combustion Symposium (International) on Combustion, pp. 256-263, 1953.

14. Burgoyne, J. H. and Weinberg, F. J., "Determination of the Distribution of Some Parameters Across the Combustion Zone of a Flat Flame," Proc. Royal Soc., A224, p. 286, 1954.

15. Levy, A. and Weinberg, F. J., "Optical Flame Structure Studies: Some Conclusions Concerning the Propagation of Flat Flames," Seventh Combustion Symposium (International) on Combustion, 1959.

16. Fristrom, R. M. and Westenberg, A. A., "Flame Structure," McGraw Hill Book Co., N. Y. 1965.

17. Pawling, J., "The Flat Flame Burner," in Experimental Methods in Combustion Research (Ed: J. Surugue), Pergamon Press, N. Y., 1961.

18. Sankar, S. V., Jagoda, J. I., Daniel, B. R. and Zinn, B. T., "Flame-Acoustic Wave Interaction During Axial Solid Rocket Instabilities," AIAA Paper No. 86-0532.

19. Rayleigh, Lord, "Theory of Sound," Dover, 1945.

20. Sankar, S. V., Jagoda, J. I., Zinn, B. T. and Daniel, B. R., "Flame Driving of Axial Acoustic Waves: Comparison of Theoretical Predictions and Experimental Observations," AIAA Paper No. 87-0219.

21. Seybert, A. F. and Parrot, T. L., "Impedance Measurements using a Two-Microphone, Random Excitation Method," NASA Technical Memorandum No. 78785, Oct. 1978.

22. Morse, P. M. and Ingard, K. U., "Theoretical Acoustics," McGraw Hill Book Company, 1968.

APPENDIX A

Professional Interactions

1) Professional Personnel:

Dr. B. T. Zinn, Regents' Professor

Mr. B. R. Daniel, Senior Research Engineer

Dr. J. I. Jagoda, Associate Professor

Dr. U. G. Hegde, Research Engineer

Mr. S. V. Sankar, Graduate Research Assistant

Mr. T. Chen, Graduate Research Assistant

2) Degrees Awarded:

Mr. S. V. Sankar, M.S.

Mr. S. V. Sankar, Ph.D. (September 1987)

Mr. T. Chen, M.S. (September 1987)

3) Refereed Publications:

i) "Rocket Motor Flow Turning Losses", AIAA Journal, Vol. 24, No. 8, pp. 1394-1396, August 1986.

ii) "The Acoustic Boundary Layer in Porous Walled Ducts with a Reacting Flow", Proceedings of the Twenty-First Symposium (International) on Combustion, August 1986.

iii) "Investigations of the Acoustic Boundary Layer in Porous Walled Ducts with Flow", AIAA Journal, Vol. 24, No. 9, pp. 1474-1482, September 1986.

4) Other Publications:

i) "Flame-Acoustic Wave Interaction during Axial Solid Rocket Instabilities", AIAA Paper No. 86-0532, January 1986.

ii) "Behavior of Simulated Solid Propellant Flames in Axial Acoustic Fields", Proceedings of the 23rd JANNAF Combustion Meeting, October 1986.

iii) "Flame Driving of Axial Acoustic Waves: Comparison of Theoretical Predictions and Experimental Observations", AIAA Paper No. 87-0219, January 1987.

iv) "Driving of Axial Acoustic Fields by Side Wall Stabilized Premixed Flames". Proceedings of the 24th JANNAF Combustion Meeting, Monterey, CA, October, 1987.

v) "Measured and Predicted Characteristics of Premixed Flames Stabilized in Axial Acoustic Fields. AIAA Paper No. 88-0541, January 1988.

5) Presentations:

i) "Flame-Acoustic Wave Interaction during Axial Solid Rocket Instabilities", AIAA 29th Aerospace Sciences Meeting, Reno, NV, Jan. 1986.

ii) "Flame-Acoustic Boundary Layer in Porous Walled Ducts with a Reacting Flow", 21st Symposium (International) on Combustion, Munich, West Germany, Aug. 3-8, 1986.

iii) "Behavior of Simulated Solid Propellant Flames in Axial Acoustic Fields", 23rd JANNAF Combustion Meeting, Hampton, VA, Oct. 20-24,1986.

iv) "Flame Driving of Axial Acoustic Waves: Comparison of Theoretical Predictions and Experimental Observations", AIAA 25th Aerospace Sciences Meeting, Reno, NV, Jan. 12-15, 1987.

v) "Driving of Axial Acoustic Fields by Side Wall Stabilized Premixed Flames", 24th JANNAF Combustion Meeting, Monterey, CA, Oct.. 5-9, 1987.

vi) "Measured and Predicted Characteristics of Premixed Flames Stabilized in Axial Acoustic Fields, AIAA 26th Aerospace Sciences Meeting , Reno, NV, Jan. 11-14, 1988.

vii) "Flame-Acoustic Wave Interaction During Axial Solid Rocket Instabilities, AFOSR Workshop on Combustion Instability, Boulder, CO., March 29-30, 1988.

viii) "Driving of Axial Acoustic Waves by Side-Wall Stabilized Premixed Flames" 22nd Symposium (International) on Combustion, Seattle, WA, August 14-19, 1988.